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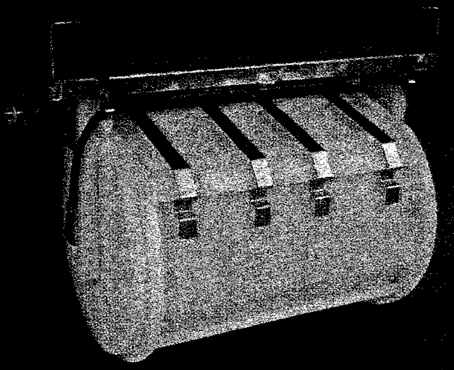

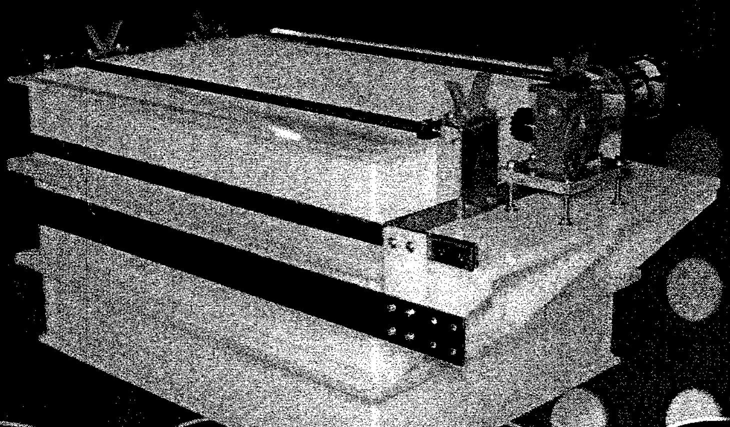

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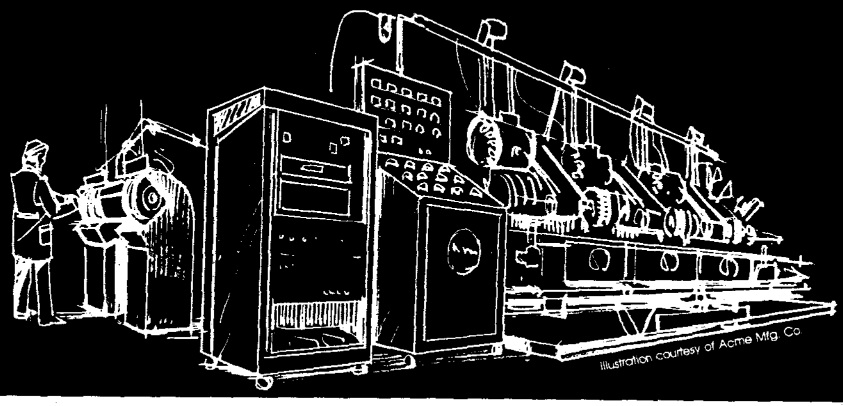


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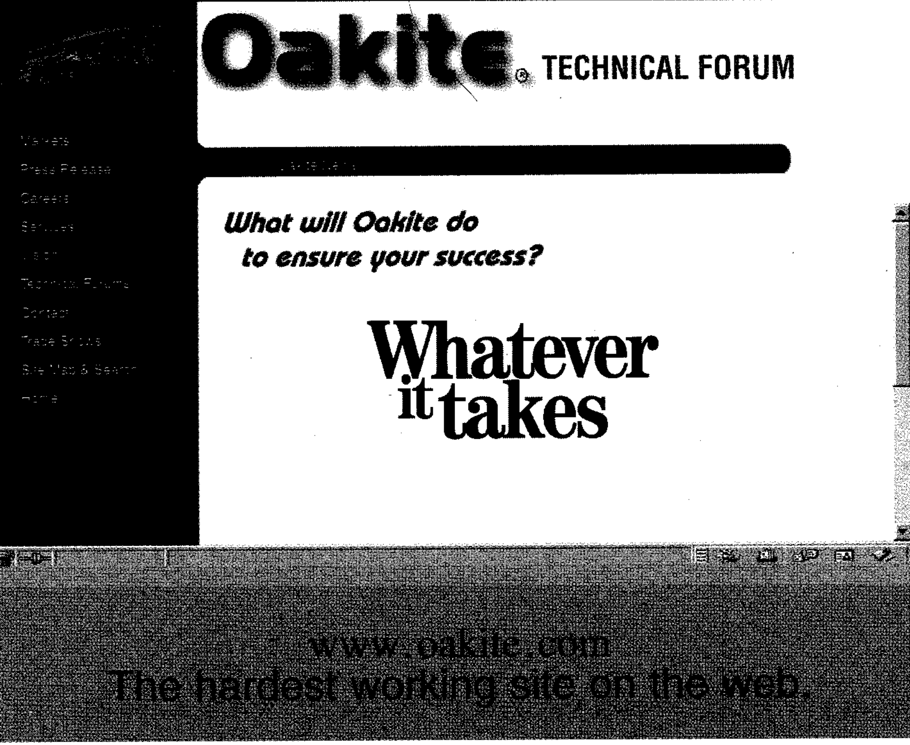
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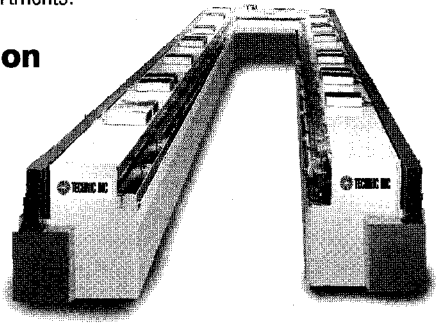
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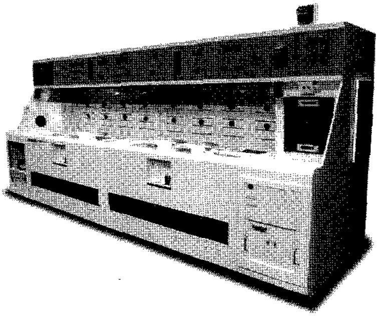

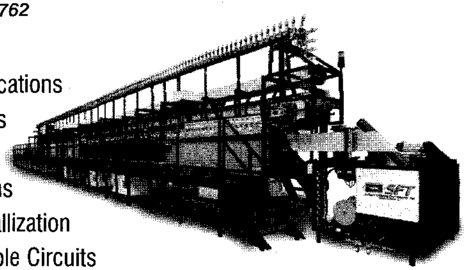
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660 White Plains Rd., Tarrytown, NY 10591
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EDITORIAL STAFF

Editor: Michael Murphy
m.murphy@elsevier.com

Associate Editor: Patti Ann Frost
p.frost@elsevier.com

Art Director/Production Manager: Susan Canalizo-Baruch
s.canalizo@elsevier.com

BUSINESS STAFF

Publisher: Eugene B. Nadel
e.nadel@elsevier.com

Advertising Sales Manager: William P. Dey
w.dey@elsevier.com

Advertising Sales Manager: Lawrence A. Post
l.post@elsevier.com

Circulation Manager: Carole Ireland
qcs1989@aol.com

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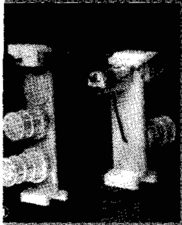

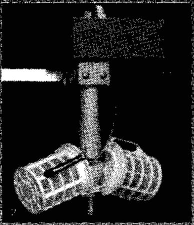

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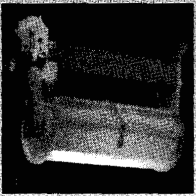

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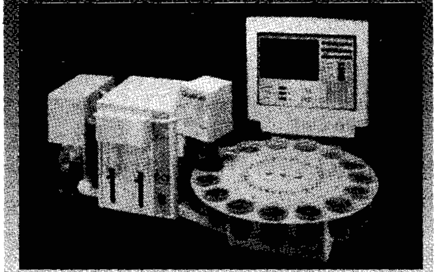

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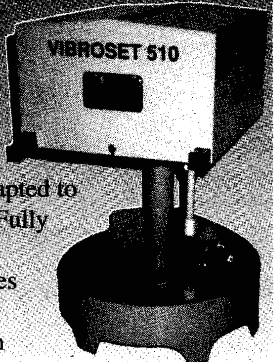

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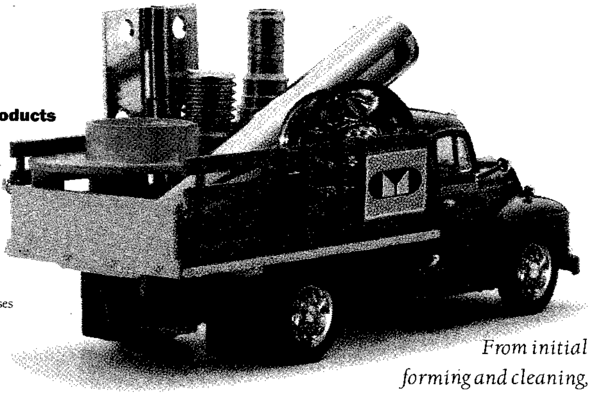

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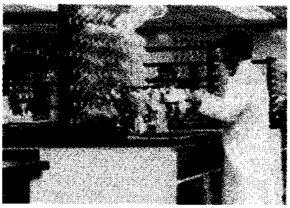

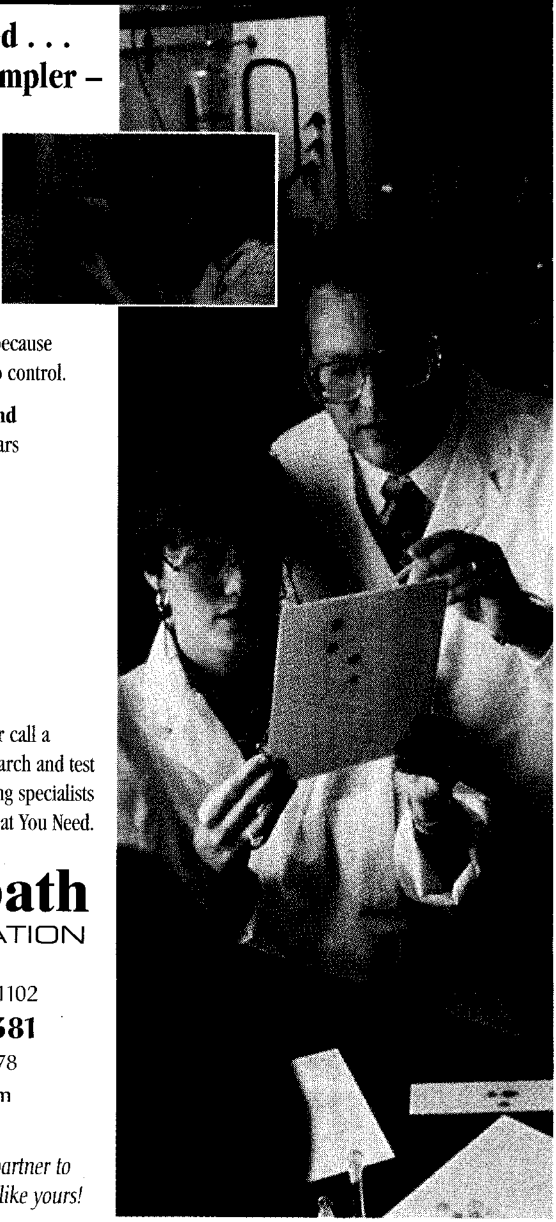

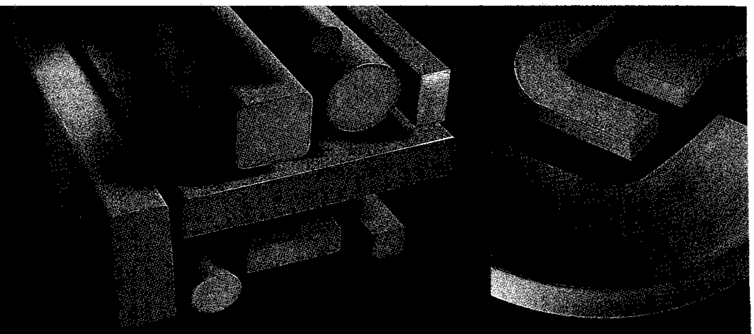

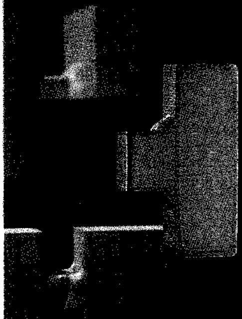


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INTRODUCTION

METAL FINISHING: AN OVERVIEW

by Leslie W. Flott

Wabash, Ind.

FINISHING BASICS

A metal is any of a category of electropositive elements, usually having a dense shiny surface. Metals are, in most cases, good conductors of heat and electricity, and can be melted or fused, hammered into thin sheets, drawn into wires, or otherwise modified by machining or forming. Metals form salts with nonmetals, basic oxides with oxygen, and may also form alloys with two or more elements: metallic or nonmetallic. The word "metal" comes from Middle English by way of French and the Latin "metallum," which in turn comes from the Greek "metallon," meaning to mine a mineral or metal.

The word "finishing" means to give a desired or particular surface texture. A finish is defined as the last treatment or coating of a surface or the surface texture produced by such a treatment or coating, or a material used in surfacing or finishing. Finishes are applied by "finishers." The word comes to us from the Middle English "finishen," which comes from the Old French "finir," "finiss" meaning "to complete" and in turn comes from the Latin "finire," from "finis," i.e., the "end."

Metal finishing thus means the application of a desired treatment, texture, or coating to the surface of a metal. Many common metals are unsuitable for a variety of applications in the form in which they are initially produced. Bare steel, raw aluminum, or copper—being quite susceptible to corrosion as they come from the mill—often have their surfaces altered in order to make them more useful. The metal finishing industry exists to supply these important surface alterations.

This *Guidebook* is a general source of information about a variety of surface modifying processes, i.e., electroplating (see the section entitled Electroplating Solutions and Plating Procedures), anodizing (see the section entitled Anodizing of Aluminum under Surface Treatments), nonmetallic finishes (see the sections entitled Chromate Conversion Coatings and Blackening and Antiquing), or mechanical finishing (see the section entitled Mechanical Surface Preparation).

The *Guidebook* can also help inform end users of what information they should provide their suppliers to enable orders to be processed in a timely and effective manner. It is equally useful to assist purchasing, engineering, and production people to understand one another's needs about what properties are necessary for a particular part. This handy reference is a ready catalog of the characteristics of the processes available. Expanded descriptions are included in the body of the *Guidebook* to provide further information about these processes including some design guidelines. The information in this *Guidebook* should be of use to metal finishers and their customers for selection of an appropriate finish for metal parts.

General Engineering Considerations

In broad engineering terms, metal finishing may be defined as any process done to protect, beautify, insulate, or increase the corrosion resistance, conductivity, or solderability of metal objects, generally of iron, aluminum, or copper alloys. Metal finishing is not, however, a haphazard process. Modern metal finishing is every bit as much a skilled operation as any other manufacturing endeavor. Most finishing problems aren't finishing problems at all; they are usually people problems. Finishing solutions must be carefully controlled as to load size and current density, with every step done in a consistent manner. Those who design parts to be plated, anodized, or otherwise treated must seek to broaden their own knowledge of the finishing processes in order to make informed decisions about finishing specifications.

There are three general categories of metal finishing: plating (including electrodeposition, electroless, and mechanical methods), anodizing, and nonmetallic coatings. Throughout the following summary will be found references to appropriate sections covering details of specific processes found elsewhere in the *Guidebook.* There are, additionally, ancillary areas of interest to all three of the categories of metal finishing. These common areas include cleaning (refer to the sections on both mechanical and chemical surface preparation), process control (covered in the section entitled Control Analysis and Testing), and finally plant engineering, safety, and waste treatment (see the appropriate chapters under Finishing Plant Engineering).

Every aspect of metal finishing worthy of concern after the parts have been finished is worthy of consideration before the parts are finished. This means that requirements must be clearly understood by the person who designs the part, the person who purchases the part, the person who finishes the part, the person who inspects the part, and the end user. If this is done, the customer will consistently receive those services needed, rather than those just thought to be wanted.

Nature of the Basis Metal

Before finishers can begin to process a part, they must know what kind of metal they are dealing with. Are the parts to be finished made of cold-roll, hot-roll, or stainless steel? If they are made of a ferrous alloy, which alloy? Have the parts been stamped or otherwise machined from wrought material or are they castings or weldments? If the parts are stamped, what is the gauge of the metal? Have the parts been heat treated? If so, is the treatment carburization, nitriding, case hardening, or some other process? If the parts are heat treated, will they require baking for hydrogen embrittlement relief before or after plating?

If the parts are made of a nonferrous metal or alloy, they will require entirely different pretreatments. Are they made of aluminum, copper, or zinc? Knowledge of the exact alloy being used is critical to successful metal finishing. Of equal importance, especially for anodizing, is not to mix alloys in the same lot or within a single weldment. Mixing alloys will always result in a less uniform finish within a lot or a single weldment, and can result in parts being destroyed.

Metal Preparation

In the preparation of metal parts for plating or anodizing, by far the most important consideration is how to clean the parts. Cleaning affects the adhesion, appearance, composition, and corrosion resistance of the final deposit. Even if the parts will receive no other finish than a dry-to-touch oil, cleaning is critical. It is, therefore, vital that the finisher be given as much information as possible about possible preexisting contamination such as inclusions in the base metal, the type and nature of the lubricants and cutting oils used in metalworking, the use or presence of synthetic organics or other coatings such as cured paints and the likely existence of inorganic films such as heat-treat scale.

Before finishers can begin to process a part, they must know what kind of metal they are dealing with. When the finisher knows what material is being finished, intelligent choices can be made. Each basis metal requires a somewhat different pretreatment. Aluminum, for example, cannot be cleaned in solutions formulated for cleaning steel. Even variation within an alloy may require modification of the pretreatment process. A wrought alloy, such as 1100,

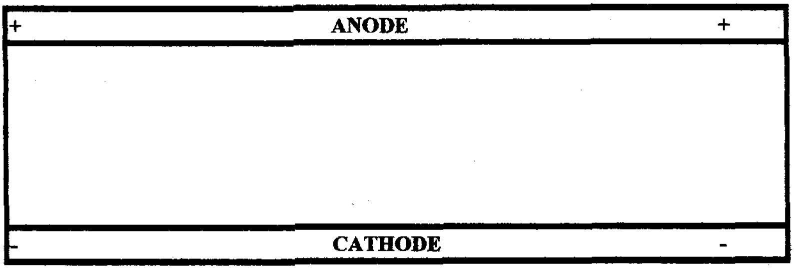

Fig. 1. How electroplating works: Metal balls or slabs are connected to the positive electrode (called the anode) in a weakly acidic or alkaline solution. The acid or base help to dissolve the metal at the anode. The solution contains the same metal as the anodes but in ionic form (that is they carry an electrical charge). As an electrical current passes through the solution, these ions migrate toward the negative electrode (called the cathode) where the object(s) to be plated is attached. The ions gain an electron at the cathode, which causes the object to attract a coating of the metal in solution. This coating builds one atom at a time in accordance with Faraday's Law, which states that 1 Faraday (96,500 coulombs) of electricity will deposit 1 gram equivalent weight of any metal. The current passing through the solution is measured in Amperes (1 A equals 1 coulomb per second).

must be cleaned differently than 380 diecast alloy. Zinc-aluminum (ZA) alloys are especially difficult to clean. Any solution that cleans the aluminum will attack the zinc portion of the alloy, and anything that will clean the zinc is likely to attack the aluminum component.

Environmental regulations (40 CFR, part 313 and others) have severely restricted the cleaning options available to metal finishers, and procedures that were common a few years ago may now be illegal or very severely restricted. ISO 14000, merely proposed at the time of this writing, may well further restrict options.

Although the choices for cleaning are more limited today, most soils and contaminants can be safely removed if the finishers know what they are dealing with. Information supplied by the customer is the key to successful metal finishing. The sections on mechanical and chemical surface preparation and Mil-S-5002 and ASTM B 322 are excellent summaries of metal preparation processes. Once the basis metal has been determined, these references should be checked for suggestions, if not requirements, for cleaning the specific material being finished.

THE ELECTROPLATING PROCESS

Electroplating is a process by which metals in ionic form migrate from a positive to a negative electrode. An electrical current passing through the solution causes objects at the cathode to be coated by the metal in solution (see Fig. 1).

The size, shape, and weight of the objects being plated determine how they will be plated.

Electroplating is done to protect, beautify, insulate, or increase the corrosion resistance, conductivity, or solderability of metal objects, generally of iron or copper alloys. Plating protects by one of two mechanisms, first sacrificially and second mechanically. Zinc and cadmium protect the base metals they cover sacrificially. They are more reactive than iron or copper alloys and, therefore, corrode first, preferentially to those basis metals. Copper, nickel,

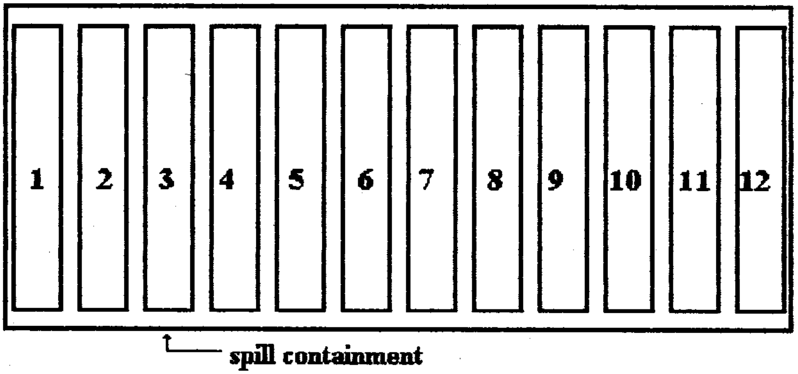

Fig. 2. A typical electroplating process: Objects to be plated are secured on racks or placed in barrels and dipped into a variety of solutions to prepare them for plating. The size, shape, and weight of the objects to be plated play a major role in determining how they will be plated. One thing is essential, however, regardless of what finish is to be applied: the parts must be "surgically" clean. Typically, more time is spent in preparing the parts to be plated than in plating them.
For a typical plating line layout the steps would be:

1: Soak clean
2: Electroclean
3: Cold water rinse
4: Acid pickle
5: Cold water rinse
6: Plating solution
7: Drag-out rinse
8: Cold water rinse
9: Chromate conversion coating
10: Cold water rinse
11: Hot water rinse
12: Dry

It should not be determined from this figure that all electroplated metals require a chromate conversion coating; however, several may require one. These would include cadmium, zinc, and sometimes silver.

chromium, tin, and most other metals provide merely mechanical protection. They protect the basis metal only so long as they themselves remain intact. If there are defects in the plating, the basis metal will corrode before the plating.

Electroplating demands as much skill as any modern endeavor. Plating baths are more sophisticated today, as are customers. Solutions must be tested regularly and the results recorded. In addition, in this day of chemical hazard awareness, the need for platers to optimize performance is greater than ever.

Platers immerse objects into a variety of chemical baths in order to change their surface condition (Fig. 2). The chemical make-up of the tanks is based on the desired result and every plating plant is different. Regardless of the finish being applied, the parts must be "surgically" clean. Typically, more time is spent in preparing the parts to be plated than in plating them.

Not only must the baths be controlled, but every step of the process as well. Although this in itself may not be different from past practice, what is different is that you are now being asked to prove conformance to customers' requirements. Verification requires not only keeping track of what is happening, but maintaining records to prove that conformance.

Brass Plating

Brass is an alloy of copper and zinc. Its origins can be traced to ancient times when the Egyptian pharaohs had death masks made from brass and gold using mercury amalgams and the plating was done mechanically. The metals were dissolved in mercury and then applied directly to a dead pharaoh's face, and the mercury was then carefully separated by the process of placing papyrus mats over the amalgam and gently tapping until the mercury (a liquid metal) separated from the other metals and passed through the papyrus, leaving the other metals behind.

Most brass plating today tends to be limited to decorative applications. See the chapter entitled Brass and Bronze Plating in the section Electroplating Solutions.

Copper Plating

Copper plating, exclusive of continuous strip plating and nickel, is the most common metal plated. It is a soft, red, ductile, and solderable surface. It is not often used as a final plate, however, because it tarnishes easily.

Copper may be plated from a variety of baths depending on the final finish desired. Probably the most commonly used is still the copper cyanide bath, which is used for both a finish coat and as an underplate or "strike," followed by another finish coating of copper or some other metal. For details on the chemistry of the many copper plating baths in current use, see the chapter entitled Copper Plating in this *Guidebook.*

The following are several good reasons for copper plating's popularity:

1. Copper is an excellent choice for an underplate, since it often covers minor imperfections in the base metal. It is easy to buff or polish copper, giving it a high gloss. This gloss greatly enhances the appearance of any subsequent overplate.

2. Copper plate is relatively inert in most plating baths of other common metals. It is about the only metal that will readily plate directly onto zinc diecasts.

3. Copper has a very high plating efficiency, resulting in excellent coverage, even on otherwise difficult parts.

4. Copper is less environmentally hazardous than many other common metals and can, under some circumstances, be recycled.

5. Copper is highly conductive, making it an excellent coating for printed circuit boards or as a coating on steel wire used to conduct electricity.

Among the most common copper plating specifications are Mil- C-14550 and GM 4252 M (copper and tin plating), now superseded by ASTM B 734 and B 545. Typically, copper will be applied at 0.0001 to 0.0002 in. (2.5 to 5.0 μm) and finish coatings for "commercial" copper plate will run 0.0002 to 0.0004 in. (5.0 to 10 μm). The upper limit of 0.0004 in. (10 μm) applies generally to externally threaded parts, but is common to most applications as well. Some automotive applications require 0.0005 in. (12.5 μm) minimum.

Note that most plating specifications are one sided, i.e., they specify only a lower limit, the upper limit is one imposed by the plater for economic reasons. A rule of thumb, provided the specific process is statistically capable, is to take the minimum thickness specified and double it in order to determine a reasonable upper limit. The target thickness may then be taken as the midpoint between the minimum and the calculated maximum.

Chromium Plating

Chrome plating is applied as a blue-white color that may be applied over underplated layers of copper and nickel for decorative purposes (see the chapter entitled Decorative Chromium Plating) or directly on the base metal for engineering purposes (see the chapter entitled Functional Chromium Plating). Chromium plate may be either shiny or dull, and often tends to highlight imperfections in the base metal. In spite of the very simple chemistry of the bath (see the chapters just listed), chromium plating is more difficult to run than many common metals, because of its very poor throwing power. Chromium does not normally throw plating into sharp inside corners and holes. The parts must be carefully racked to avoid being shaded-out by the rack. In cases in which design does not allow complete coverage, the nickel underplate will show through the chromium with a slightly yellowish color. Among the most common chromium plating specifications are ASTM B 456 (actually copper/nickel/chromium) and federal specification QQ-C-320.

Decorative chromium is normally applied over copper and nickel [normally > 0.0002 in. (5 μm) copper and > 0.0003 in. (7.5 μm) nickel] as a very thin coating typically 0.000050 in. (1.0 μm). The appearance of the final parts is usually determined by the underplate and is not the exclusive result of chromium plating. Specification QQ-C-320—"Chromium Plate"—calls for either Class 1–Decorative, Type I–Bright, or Type II–Satin.

Hard chromium is applied for wear resistance or to restore an old worn part to its original dimensions. It is generally applied directly onto the base metal. The appearance of hard chromium varies with the substrate onto which it is plated and can range from semibright to dull gray. A common chromium plating specification is AMS 2406, "Chromium–Hard Deposit–On Ferrous Metal Parts," and QQ-C-320–"Chromium Plate" Class 2–Engineering, and ASTM B 177. Engineering (hard) chromium may be applied in thicknesses up to significant fractions of an inch, but the default thickness is 0.002 in. (50 μm), unless the customer specifies otherwise.

Other chromium plating specifications include Mil-C-14538, Mil-C-20218, and Mil-C-23422, all of which specify essentially special purpose coating.

Nickel Plating

Nickel plating is a yellowish white, hard, reflective finish used for wear resistance, solderability, or dimensional restoration. Nickel plate is often applied over copper and under chromium for a decorative finish. Nickel is a very hard metal with relatively poor ductility; consequently, parts to be nickel plated should be bent into final shape before plating whenever possible. The chapter entitled Nickel Plating covers both decorative and engineering applications of nickel.

Bright nickel plating is a highly reflective finish, which often eliminates the need for subsequent polishing. Bright nickel may be applied as a single or multilayer coating, though caution must be taken when attempting multilayer nickel, as it may result in poor adhesion in some instances. Multilayer nickel is favored for its excellent corrosion resistance.

For applications requiring bright nickel, there are other considerations. The brighter the nickel plating, the greater the internal stresses and the lower the ductility. The brightest finishes result from first polishing the base metal substrate. It is best to avoid specifying bright nickel if the parts are to be bent or crimped after plating.

Semibright nickel has a more satiny finish than bright nickel and may be marginally more ductile. If heat shock or minor bending of the parts is anticipated it would be better to specify semibright nickel in order to reduce the risk of the plating flaking off.

Nickel may be specified by QQ-N-290—Nickel Plate, Class 1–"Decorative," Types I to III are for steel parts and Types V to VII for copper-base parts and ASTM B 456, "Copper/Nickel/Chromium" for a variety of service classes (SCs), which vary with alloy and base metal. The thickness of nickel plating for most commercial applications will be 0.0002 to 0.0004 in. (5 to 10 μm), but since nickel plates readily, it may be plated to hundreds of an inch (500 to 600 μm is easily possible) in some engineering applications.

Silver Plating

Silver plating, in addition to being decorative, has the highest electrical and thermal conductivity of any metal. Silver may be plated from a noncyanide bath, but more typically is plated from a cyanide bath. See the section entitled Electroplating Solutions, specifically the chapter entitled Silver Plating for details on silver plating baths. Silver plating is highly ductile, malleable, and solderable. Silver tarnishes easily, however, due to sulfides in the air and should be packaged with special tarnish-resistant paper. Silver can be plated to military specification QQ-S-365, "Silver Plate" as Type I (matte finish, the best conductor), Type II (semibright) or Type III (bright, the worst conductor) and may call for Grade A (chromate treated) or Grade B (no chromate).

Matte silver plate (QQ-S-365, Type I) is used extensively for finishing electronic components where silver's mechanical, electrical, and thermal properties offer distinct advantages over other metallic, even silver, finishes.

Semibright silver plate (QQ-S-365, Type II) is often specified where the electrical and/or mechanical properties of silver plate alone may not be enough and the design engineer feels that appearance may also be an important consideration. Semibright silver does, however, tend to tarnish faster than matte silver.

Typically, platers prefer to apply silver plate as thin as practical, because it is a relatively expensive metal. Designers, of course, specify the thinnest plating that will serve their purposes, but anything over that minimum is "free." Precious-metal plating is thus controlled much more closely than are the more common metals. Silver is typically applied in thicknesses as low as 0.00005 to 0.0005 in. (1.0 to 10 μm), although most applications call for 0.0002 to 0.0004 in. (5.0 to 10.0 μm).

Finishes for Stainless Steel

Passivation of stainless steel is not electroplating, it is a nonelectrical process whereby the free iron is chemically removed from the surface of stainless steel. This prevents the formation of possible corrosion sites and the development of tightly adhering oxides. The 300 series alloys are generally preferred for passivation, as some of the 400 series alloys will actually be discolored by the passivation process. Passivation imparts a limited neutral salt spray corrosion protection to the stainless steel, usually not much over 2 hours. It is critical when making assemblies to be passivated that all component parts be made of the same alloy; different alloys may be indistinguishable before passivation, but may have a different appearance afterward. Since different solutions are used to passivate different alloys, they must be properly identified. Mixing alloys may not only result in differences in appearance, but may result in some parts being destroyed. Passivation of stainless steel is generally specified by QQ-P-35 or ASTM A 380.

Plating on stainless steel may be done, after suitable pretreatment, by any method listed here. Stainless steels and high-nickel alloys form a tightly adhering passive oxide film within minutes of being plated. Stainless parts can be plated with other metals if a fresh active surface is provided for subsequent plating (see the section of the *Guidebook* entitled Preparation of Basis Metals for Plating. Plating on stainless steel is addressed by ASTM B 254.

Tin Plating

Tin plating is normally done to impart solderability to a variety of base metal substrates. Tin is a silvery blue-white metal that is ductile, solderable, and covers very well. The solderability of tin can be affected by the substrate, since several metals tend to react with and migrate into the tin forming relatively nonsolderable intermetallic layers. Of particular concern is that if the tin is to be plated over brass, or zinc die casts, the zinc will migrate into the tin and severely limit the shelf life of the finished parts. The migration can be mitigated by the common practice of applying an undercoating of copper or nickel through which the zinc cannot migrate.

Tin is a fairly easy metal to plate and is approved for a variety of industrial applications and is even approved for food-container or food-contact applications. There are no known common tin salts that are extremely toxic or carcinogenic. Tin does not tarnish easily, making it a good choice as a low-cost decorative finish as well.

Tin plating is addressed in Mil-T-10727. Although this specification calls for a fairly thin plating for solderability (0.0005 in. or 1 μm), common practice is to apply much more. This thinner plate was commonly used when "stannate tin" baths were in common use and practice was to reflow the tin periodically. The tin plate from these older-style tin baths tended to change spontaneously from "white" tin to "black or gray" after a few months, hence the need to reflow the tin. This process also caused not a few fires. Today, where long-term shelf life is a consideration, 0.0003 in. (7.5 μm) minimum tin is commonly used over an underplate of 0.0002 in. (5.0 μm) minimum copper or nickel.

There are a great many other specifications calling for tin combined with other metals being plated as an alloy. These include Mil-L-46064 and Mil-P-81728, both of which are for tin-lead, and Mil-P-23408, tin-cadmium. Tin may also be plated as a tin-nickel alloy, which is sometimes used as a substitute from decorative chromium. All of these alloy finishes generally offer a better shelf life than pure tin plate, but are considered environmentally unfriendly, and so their use is much diminished.

The tin and tin-lead alloy plating baths are discussed in the chapter entitled Tin-Lead, Lead, and Tin Plating; and tin-nickel is discussed in the chapter entitled Tin-Nickel Alloy Plating.

Zinc Plating

Zinc plating is a soft, ductile, decorative, marginally solderable, corrosion-resistant finish. Unlike most other commonly plated metals, zinc protects the substrate by sacrificing itself and thus corrodes before the base metal. This means that zinc will protect even if the zinc coating sustains minor damage, such as scratches of small punctures, which is often an advantage that other types of plating do not offer. Zinc is the most reactive of all common metals; however, it may be attacked or dissolved by ordinary liquids such as soft drinks and vinegar. The ultimate corrosion resistance of zinc is a function of the plating thickness. To increase the corrosion resistance of zinc, a conversion coating is usually added.

In the chapter entitled Zinc Plating, the authors discuss the three most common zinc plating baths in use today. They also examine the relative merits of these popular zinc plating baths. Additionally, the chapter entitled Zinc Alloy Plating looks at zinc-iron, zinc-cobalt, zinc nickel, and tin-zinc alloy baths, which have become increasingly popular both because of their remarkable corrosion resistance and as a possible substitute for cadmium.

Chloride zinc plating was introduced about 1980, when environmental pressures began to demand the replacement of cyanide plating baths with noncyanide baths. Presently, over 50% of all zinc deposited in this country is from acid chloride baths. By far, the majority of these are chloride baths with potassium chloride and are ammonia-free with a pH around 5 to 6. These baths have high cathode efficiency and excellent throwing power because of the high cathode efficiency over the entire current density range.

The most commonly used specification for zinc plating is ASTM B 633, which replaced QQ-Z-325 in 1982, although a great many drawings still call for QQ-Z-325. One of the main advantages of the ASTM specification over QQ-Z-325 is that ASTM B 633 distinguishes between colored and clear chromate conversion coatings. It calls out four types of post finishes for zinc plating, Type I: as plated; Type II: colored chromate (default yellow, but olive drab or black may be specified); Type III: colorless chromate (these are often designated as clear or bright, blue bright, or blue); and Type IV: phosphate coating. Thicknesses are spelled out by an SC designation: SC1, 0.001 in., SC2, 0.0005 in., SC3, 0.0003 in., SC4, 0.0002 in. and SC5, 0.0001 in.

Chromate Coatings

Chromate conversion coatings are chemical conversion coatings. The substrate metal participates in the coating reaction and becomes a component of the coating. The collaboration has a profound effect on the properties of the coating. Among the metals commonly chromated are zinc, zinc die castings, hot-dipped galvanized steel, aluminum, and sometimes copper and silver. Chromate films are typically very thin, on the order of 0.0000001 in. and contribute no measurable thickness to the overall coating.

The chemistry involves a reaction between the metal surface and an aqueous solution containing chromates (chromium salts, either hexavalent or trivalent) and certain activators or film formers. Activators may include sulfates, fluorides, phosphates, and sometimes complex cyanides. Normally, a given chromate is designed to work on a particular metal, but in a few cases will work on two or more. The chromate solution is normally acidic. About 0.0005 in. of plating thickness is dissolved during the chromating process.

Clear chromate offers from 8 to 12 hours' resistance to white corrosion (zinc oxide or "white rust") and has a clear to slightly iridescent blue appearance. This is one of the earliest types of chromating solutions and is used today. Older style "clear" chromates often deposited as a golden yellow coating and were then bleached by immersion in a dilute alkali solution to obtain the clear appearance.

More up-to-date blue bright chromates are single-dip solutions, often using only trivalent chromium salts and are, therefore, more environmentally friendly. Some varieties of this type of baths may be dyed a variety of colors. These colors are often used for identification purposes.

Gold, or yellow, chromate coatings are deposited from baths that contain chromate, sulfate, or chloride activators and produce a distinct iridescent golden yellow color. Yellow chromates contain more hexavalent chromium than clear films, which accounts for their color. Yellow chromate offers in excess of 96 hours' neutral salt spray corrosion protection and is an excellent paint base.

Olive drab, or forest green, chromate is the ultimate in commonly available conversion coatings, with neutral salt spray resistance in excess of 150 hours. This chromate is most commonly specified for military applications. It is generally not possible to apply to barrel plate work. The color and the corrosion resistance are due to the inclusion of an organic acid modifier to the chromate formula. Many customers find the color is not especially pleasing, but specify it for nonmilitary applications for its functional, rather than its decorative, value.

Black chromate is usually achieved by incorporating a soluble silver salt in a golden chromate formula, which produces a deposit of black silver chromate. This coating offers excellent corrosion resistance and a jet black semimatte to matte appearance. Black chromate has even found some applications in the space program, in which it is used on solar collectors.

The use of silver salts makes black chromate coating rather more expensive and is also sensitive to chloride contamination. This is especially a problem when black chromate is to be applied over parts plated in a chloride bath.

Chromate conversion coatings are included in a great many specifications and are also covered in their own specification Mil-C-5541, although that specification applied exclusively to chromate conversion coatings on aluminum.

Special Processes

Special processes include a variety of finishes that do not change the surface of the parts other than through chemical or mechanical means.

Pickle and oil uses an acid solution to remove scale and rust from the metal surface, after which a special rust-inhibiting oil preservative is applied to prevent or retard further corrosion. Some steels with very high polish or microfinish may show a reduction in gloss as a result of the pickle and oil process. Caution is recommended. Rust can also significantly reduce the gloss or microfinish on steel parts.

Chemical etch is used on iron, copper, and aluminum to remove metal chemically, thus creating a more uniform matte finish than is found on the as-produced material. Chemical etching has the disadvantage of preferentially attacking high-energy areas, such as sharp corners and threads. The result can be the rounding of these corners, etc., which may not always be desirable. Chemical etching is not a "polishing" process and cannot be used to remove deep scratches or tool marks from the metal surface. Typically less than 0.0005 in. of material is removed by the chemical etch process. Since these effects are different for different alloys and even different steel production processes (hot-roll versus cold-roll), it is important

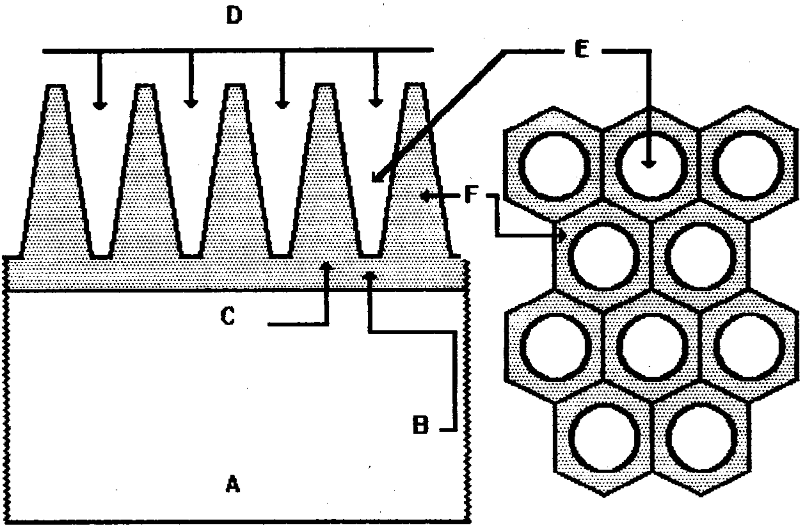

Fig. 3. The anodize process: The aluminum base metal, A, reacts with the oxygen at B, forming an aluminum oxide coating. This dense layer of newly formed aluminum, C, is dissolved by the acidic electrolyte, causing the layer to become porous at D. The result is a relatively large pore, E, and a fairly thin cell wall, F. When the forward film building process is in equilibrium with the dissolution of the coating, the anodize coating stops getting thicker.

for the customer to advise which alloy is to be treated. It is equally important that alloys not be mixed, either within a lot or within a single weldment or assembly.

Hydrogen embrittlement relief is done after plating to remove hydrogen from the intercrystalline interstices, which could otherwise result in brittleness and premature failure of the part. The process is typically applied to fasteners, springs, and other parts having a Rockwell C (R_c) hardness of 30 or higher. The process must also be done within 1 hour of the plating process. Hydrogen embrittlement relief is generally done at 190 ± 5°C and is, therefore, achieved without annealing the parts.

ALUMINUM FINISHING

Anodizing is an electrochemical process whereby the naturally occurring oxide coating on the outer surface of an aluminum part is changed to a tightly adhering layer of oxide of aluminum of a specified thickness. The natural coating is approximately 0.0000005-in. thick, but the anodizing process can increase the coating to a film thickness of 0.0005 to 0.003 in. This thicker coating is much more resistant to corrosion and abrasion than the underlying aluminum. Anodizing coats very uniformly and will, therefore, not fill or smooth out a rough or damaged surface.

In anodizing, there are two competing processes that occur simultaneously. Aluminum parts are first made the positive pole, or anode, in an electrochemical cell using an acidic electrolyte. As current passes through the solution, oxygen is generated at the anode and immediately reacts with the aluminum parts to form an aluminum oxide coating. Simultaneously, the aluminum oxide coating is dissolving into the electrolyte and is becoming porous

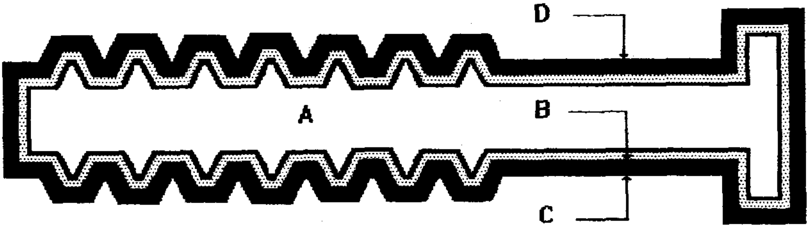

Fig. 4. Cross section of an anodized bolt: In the illustration, the bolt is made of aluminum, A, with its original surface at B. The anodize not only builds to a new surface at D, but also penetrates A by a nearly identical amount. This penetration depth, C, plus the build up, equals the total anodize film thickness.

and less dense. When these two competing processes are in equilibrium, the anodized coating reaches its maximum and can no longer become thicker (see Fig. 3).

Anodizing does not simply add material to the base metal as does plating. The anodized film grows outward and also penetrates the aluminum base metal, each by approximately one-half of the overall film thickness. Since each side grows by an amount equal to one-half the anodized film thickness, the part grows an amount equal to the total anodized film thickness (see Fig. 4).

Anodized aluminum has many useful engineering properties. For example, anodizing offers excellent corrosion resistance, typically over 336 hours' salt spray resistance (tested per ASTM B 117) and a surface that is second only to that of diamond in hardness. Note, however, that the anodized film is rather thin and doesn't have a great deal of puncture resistance. Anodize hardness is normally expressed in terms of its ability to resist abrasion (tested by the Tabor Abrasion Test). Anodize must be sealed in order to obtain optimum corrosion resistance.

Frequently, designers of electronic devices are inspired by the thought of using anodized aluminum for heat sinks. The idea is very appealing, since aluminum is a very good heat conductor and anodize is a dielectric. The idea of a dielectric thermal conductor is too good to pass up. This never works, however, because of the nature of anodizing. Anodizing, unlike electroplating, works from the surface inward. The coating grows outward from the interface between the anodic coating and the raw aluminum. The growth is at right angles to the surface of the base metal, i.e., perpendicular. The coating is forming around a three-dimensional object, but cannot itself grow in three dimensions. The result is cracking at sharp corners. A thin anodic film will not crack to any great extent; however, the thicker the film, the worse the cracking becomes. Hardcoat anodize tends to crack more than sulfuric anodizing, for two reasons: first the hardcoat tends to be denser than clear (sulfuric) anodizing, and hardcoat films are generally thicker than clear anodizing. In order the minimize this corner fault, all edges should be radiused at least 0.030 in. for each 0.001 in. of coating thickness (see Fig. 5).

Steel or brass inserts, or any material other than aluminum, that are part of an assembly or weldment submitted to be anodized must be removed or masked before anodizing. Unless removed or masked, the inserts will probably be destroyed by the anodize process.

Because most anodized coatings are porous, they are able to absorb dyes before they are sealed. This produces an attractive colored oxide coating integral to the metal itself, and is less likely to chip or peel than plated coatings. With proper care and handling, anodized articles can last a lifetime.

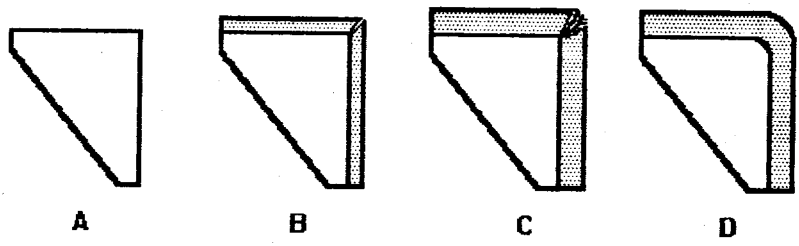

Fig. 5. Corner faults: A plain piece of aluminum, A, may be formed with sharp corners without any problems. Corners, however, create a special problem when the aluminum is anodized because anodizing builds from the inside out. When a thin anodize film is formed, stresses build at the outside corners until eventually the corners crack, as shown at B. The thicker the anodize, the greater the severity of cracking, as shown at C. These corner faults can be minimized by radiusing the corners as shown in D.

On threaded parts, the pitch diameter is measured over four separate surfaces; the apparent growth of the pitch diameter is, therefore, approximately equal to the thickness of the anodized film.

Common Types of Anodizing

Chromic anodize is the oldest type of anodizing and applies the thinnest film. Rarely will chromic anodize apply more than 0.0002 in. to wrought alloys, and less to a cast alloy. Chromic anodizing is normally a grayish coating formed from a chromic acid electrolyte. Chromic anodizing is most often used as a base for paint for aircraft and marine applications. It has been phased out of many operations because of environmental considerations.

Sulfuric anodizing, also called clear anodizing, is an excellent corrosion-resistant finish and, under the right circumstances, a good electrical insulator. This is the most common type of anodizing done today. Sulfuric acid anodizing may exhibit a silver, bronze, tan, or gray color, depending on the alloy used. The coating is commonly dyed, or otherwise colored, with a variety of organic dyes, mineral pigments, or precipitated metals. Typically, a sulfuric anodizing coating will be from 0.0005 to 0.0015 in. for wrought alloys and a bit less for cast alloys.

Hardcoat anodizing is an highly abrasion-resistant, nonconductive coating of aluminum oxide ($Al_2O_3 \cdot H_2O$) that makes the aluminum surface harder than tool steel. Hardcoating is done in a sulfuric acid electrolyte modified by the addition of one or more organic acids and is run at very low temperatures. Typically, the R_c hardness will be in the 65 to 70 range. To obtain maximum wear resistance, the hardcoat should not be sealed. The nominal thickness of hardcoat runs from 0.002 to 0.003 in. on wrought materials and less on most cast alloys.

Weldments and Welded Parts

Welds on aluminum are often porous; acid is trapped in the welds and the narrow spaces between the parts. It may take upward of 24 hours for the acid to begin to leach out and attack the anodized coating or bleach the dye. This will continue until all of the entrapped acid has seeped out.

Hollow parts (pipes, square tubing, etc.) can hold a lot of acid and act as a reservoir. The stored acid poses a potential danger to end users or others who may handle the parts at a later time. It is, therefore, critical that ¼-in. minimum drain holes be drilled into each chamber that might potentially store acid. Drains will allow the acid to bleed out and be replaced by clear water during the anodizing process.

The high temperatures required by the welding process will affect an area around each weld, causing the color to be slightly lighter and causing the welded area to appear larger than it actually is.

Choice of Alloys for Anodizing

Anodizing is recommended for virtually all aluminum alloys. It is critical, however, that alloys not be mixed in a weldment, or within a single order. Alloys such as 2024 if mixed or welded to 6061, for example, may well be totally destroyed during the anodizing process.

Wrought Alloys

1100 series alloys yield a bronze to gray coating at 0.002 in. The alloys are particularly soft and do not machine well. The maximum coating that can be expected is 0.0025 in., but 0.003 in. is possible.

2000 series, principally 2011, 2017, 2024, and 2618 (forgings), develop a gray-black to blue-gray color at 0.0025 to 0.003 in.

3000 series, most commonly 3003, develops a gray-black color at 0.002 in. They machine well and readily take dye.

4000 series is not commonly used for anodizing.

5000 series, primarily 5005 and 5052, machine well and are good for dyed work. They develop a black color at 0.002 in. This material when hardcoated has excellent dielectric properties.

6000 series, most commonly 6061 and 6063, form excellent anodized coatings. Hardcoat on these alloys may be ground, lapped, or honed. The alloys have excellent dimensional stability and machine well, though they can be a bit stringy under some circumstances. The 6063 is commonly used for extrusions and as rod for welding other alloys. The maximum practical coating thickness is 0.0025 in.

7000 series (usually only 7075 is commonly used) develop a blue-gray color at 0.002 in. It is not a good choice for grinding or lapping, since it has a tendency to be checky.

8000 series is not commonly used for anodizing.

Cast Alloys

Alloys for sandcasting commonly include 319, 355, 356, and sometimes 40E (a ternalloy). The 356-T6 is the most commonly used sandcast alloy because it grinds and polishes well. Porosity is always a problem with sandcastings. Pores will cause the coating to appear to have pits. Anodizing will not fill the pores. Sandcast parts are commonly coated to 0.001 to 0.002 in., but some will develop thicker coatings.

Alloys for diecasting include 218, 360, and 380. Of these, only 218 produces an anodized coating comparable to wrought or sandcast alloys. The 218 is hard to diecast, however, so is rarely used.

Reanodizing Parts

Anodized coatings of any type—chromic, sulfuric, or hardcoat—cannot be built up over existing coatings. Once electrical contact with the anodized part has been broken it is very difficult to reestablish it. Stripping and reanodizing works but removes metal and, therefore, affects critical dimensions. Stripping and reanodizing may produce parts that are dimensionally unusable as a result. As a matter of policy, stripping and reanodizing are done only with specific customer approval.

Coating Thickness

The coating thickness for any type of anodizing is roughly 50% buildup and 50% penetration. In other words, a 0.002-in. coating thickness will build up only 0.001 in. per side. This means that the overall dimension of the part increases by an amount equal to the total film thickness. Holes are closed by a like amount, unless plugged or masked.

Hardcoat may be provided in a thickness ranging from a few tenths of a thousandth of an inch up to about three thousandths of an inch. As stated above, hardcoating (and indeed all anodizing) changes the dimensions of a part by an amount equal to one-half of the combined total buildup on opposite sides of a part. When machining parts to be hardcoated, or anodized, it is essential to allow for this change and to specify a coating thickness on blueprints and purchase orders.

Masking

When it is necessary to exclude the anodize from specific areas, the parts can be masked. Areas to be masked, such as threaded holes, ground points, etc., must be clearly identified by the customer. Masking is a hand operation, which may add to the total cost of anodizing a part. Even if anodizing is required on only one area of a part, it may be cheaper to anodize the entire part rather than pay for the masking. On the other hand, it may be cheaper to tap holes and mask them, rather than purchase special drills and taps and try to do the job after anodizing.

Racking

The anodized coating that builds up on the part is an excellent insulator. Firm electrical contact must be made with the parts to be anodized and these "rack marks" will not have any anodize on them. Proper racking is the key to economical and effective anodizing. It is essential that the rack marks be located in a noncritical area. Any guidance as to where to locate these small bare spots will aid in the proper processing of the parts and, in the absence of such guidance, good practice should be followed. Occasionally, good practice may place the rack marks in an unidentified critical area in spite of best intentions. Parts should never, however, be racked in threaded holes without specific instruction from the customer.

Polishing and Lapping

Norbide (boron carbide) or equivalent abrasive grain using a heavy oil or petroleum jelly carrier cuts very fast with excellent results. The use of polishing sticks or brushes is recommended. A grit size of 400 to 1,200 works well depending on the finish required.

Grinding

Norton Crystolon (silicon carbide) abrasive or its equivalent is most satisfactory for surface grinding hardcoat. Eighty to 100 grit will yield a microfinish of 2 to 8 microinches. Soft wheels in H, I, or J grades are preferable for fast stock removal and their use minimizes the danger of burning or cracking. Typical wheel numbers are 39C60-J8VK for finishes of 6 to 10 microinches and 39C100-H8VK for finishes of 2 to 3 microinches. Cylindrical grinding is best done with a 39C120-J8VK. This finer grit wheel will be free cutting and still produce a very fine finish. For internal grinding, the 39C100-J8VK gives the best results.

In general, grinding hardcoat should be done wet, using water as a coolant and a good quality medium-priced soluble oil mixed approximately 100 to 1. Cincinnati Cimplus has been used at 200 to 1 with good results.

Hardcoat and Teflon

Teflon may be added to hardcoat as a posttreatment to provide a hard, corrosion-resistant, dry-lubricated, low-friction surface.

Chromate Conversion Coatings

Chromate conversion coatings may be applied to aluminum from a chemical bath. All chromates on the QPL list should be considered interchangeable, and the same materials are generally approved for both clear (used for low contact resistance) or golden yellow per Mil-C-5541.

The clear chromate is a nearly colorless coating that has excellent salt spray corrosion resistance (168 hours tested per ASTM B 117), with a typical contact resistance of less than 500 micro-ohms.

Yellow, or golden, chromate is used most often for corrosion resistance and to increase subsequent paint adhesion. Parts with yellow chromate are normally (more frequently when required) tested monthly by an independent laboratory by Federal Test Standard 141 A. By specification, the color of a nominally yellow chromate conversion coating can vary from very light yellow to brown. Some variation of color from part to part and even within a single part is normal and acceptable per the above specification.

Plating on Aluminum

Plating on aluminum is different from conventional electroplating because of the unique nature and reactivity of aluminum. The principal pretreatment involves the removal and subsequent prevention of the natural surface oxidation. Since an oxide film forms in seconds on a freshly cleaned aluminum surface, it is necessary to apply an immersion coating of zinc, temporarily, to prevent this oxidation. This coating, called "zincate," is removed in the next plating step (usually copper plating) after which the aluminum can be plated the same as any other metal.

MECHANICAL SURFACE PREPARATION

POLISHING AND BUFFING

by Al Dickman

Jackson Lea, a Unit of Jason Inc., Waterbury, Conn.

POLISHING

Mechanical finishing refers to an operation that alters the surface of a substrate by physical means such as polishing and buffing.

Polishing plays a vital role in the development of a quality product. The term polishing is not to be confused with buffing. The definition of polishing is surface enhancement by means of metal removal and is generally done by an abrasive belt, grinding wheel, setup wheel, and other abrasive media. A definite coarse line pattern remains after such a polishing operation. This polishing effect removes large amounts of metal from a particular surface.

Buffing is the processing of a metal surface to give a specific or desired finish. The range is from semibright to mirror bright or high luster.

Polishing refers to an abrading operation that follows grinding and precedes buffing. The two main reasons for polishing are to remove considerable amounts of metal or nonmetallics and smooth a particular surface. This operation is usually followed by buffing to refine a metallic or nonmetallic surface.

POLISHING WHEELS

Polishing wheels can be made up of a different variety of substrates such as muslin, canvas, felt, and leather. Cotton fabric wheels as a class are the most commonly used medium for general all-round polishing due to their versatility and relatively modest cost. Polishing wheels can have a hard consistency, such as canvas disks, or a soft consistency, such as muslin, sewn together. The most popular wheels are composed of sewn sections of muslin disks held together by adhesives. The types of adhesives used include those with a base of silicate of soda and the animal-hide glue type.

Felt wheels are available in hard densities to ultrasoft densities. The outside periphery or face of the wheel must be kept true and be absolutely uniform in density over its entire surface. Felt wheels can be easily contoured to fit irregularly shaped dimensions. Felt wheels are generally restricted to use with finer abrasive grain sizes.

In general, the more rigid polishing wheels are indicated where there is either a need for rapid metal removal, or where there are no contours and a flat surface is to be maintained. Conversely, the softer types with flexibility do not remove metal at such a high rate.

In addition to polishing wheels, precoated abrasive belts can be obtained in any grit size ready for polishing operations. Metallic and nonmetallic articles are polished on such belts running over a cushioned contact wheel with the proper tension being put on them by means of a backstand idler. Where a wet polishing operation is desired, the use of abrasive belts in wet operations needs to have a synthetic adhesive holding the abrasive particles to the belt backing. This synthetic adhesive must have a waterproof characteristic.

BURR REMOVAL

The removal of burrs is a breaking of sharp edges. Burr removal is done by the following methods: hand filing, polishing, flexible polishing, satin finishing, brushing, and tumbling. Functional parts do not necessarily need a decorative finish and usually deburring becomes the final mechanical finish.

Burrs can be removed by hand methods such as filing, which is very labor-intensive making mechanical means preferred in most cases. Parts that contain restricted areas can be processed using set-up polishing wheels and muslin buffs coated with a greaseless compound. See the discussion on polishing wheels (above) and buffing. Processing methods will be determined by the configuration of the part. If a part contains a heavy burr yet the edges are straight, a rigid set-up wheel is needed. Where the contours are irregular and the burrs not excessive, a sewn or loose cotton buff with a greaseless compound works more efficiently. If extreme flexibility is required, a string wheel with greaseless compound or a tampico wheel with aluminum oxide, grease-based material is required.

BUFFING

Buffing is the processing of a metal surface to give a desired finish. Depending on the desired finish, buffing has four basic categories: satin finishing, cutdown buffing, cut-and-color buffing, and luster buffing. Satin finishing produces a satin or directional lined finish; other types of satin finishing are brushed or Butler finishing. Cutdown buffing produces an initial smoothness; cut-and-color buffing produces an intermediate luster; and luster buffing (color buffing) produces high reflectivity or mirror finish.

TYPES OF BUFFING COMPOUND COMPOSITIONS

Greaseless compound is used to produce a satin finish or a directional lined finish. Greaseless compound contains water, glue, and abrasive. As its name implies, it retains the abrasive on the buffing wheel in a grease-free environment, leaving the surface of the finished part clean and free of greasy residue. The principal uses of greaseless compound are for satin finishing or flexible deburring.

Generally, the abrasive contained in such compounds is silicon carbide or fused aluminum oxide. Grades are available in abrasive sizing from 80 grit to finer depending on the degree of dullness required on a particular base metal. Silicon carbide abrasives are used for the finishing of stainless steel and aluminum. Aluminum oxide grades are used for brass and other nonferrous metals, as well as for carbon steel prior to plating.

To produce a finer satin finish on nonferrous materials, fine emery and hard silica are used. For Butler finishes on silver plate and sterling, fine buffing powders of unfused aluminum oxide and soft silica are used. Greaseless compounds are applied to a revolving buff by frictional transfer. The buff speed is 4,000 to 6,000 surface feet per minute (sfm). The material then melts on the cotton buff, adheres to the peripheral surface, and dries in a short

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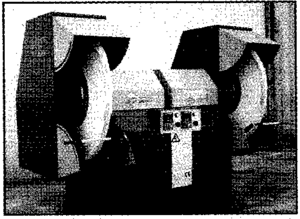
4263 RAYMIR CIRCLE - WAUWATOSA WI-USA 53222-1139
Tel.: 011 39 0307721850 - Fax.: 011 39 0307240612
INTERNET - http://www.deantoni.it - E-mail dantech@deantoni.it

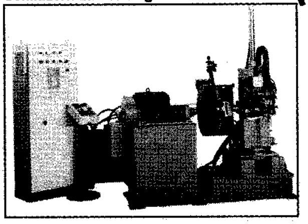
POLISHING AND BUFFING MACHINES

ALUMINIUM
BRASS
STEEL
GOLD
SILVER
STAINLESS STEEL
ZINC
ALLOYS
WOOD

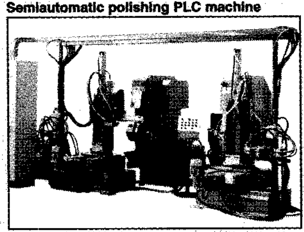
Manual buffing machine



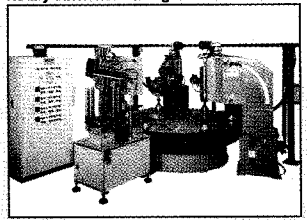
Semiautomatic buffing PLC machine



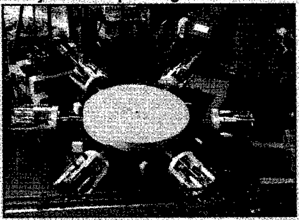
Semiautomatic polishing PLC machine



Rotary automatic buffing machine



Rotary automatic polishing machine



CNC buffing machine

Single robotic workcell

Multiple robotic workcell

Dan Technology
is an Italian Company.
The address in WI is:
ATI, Inc.
4263 Raymir Circle
Wauwatosa, WI
US 53222-1139
Phone: 414-463-8687
Fax: 414-463-3030

FROM OUTSIDE U.S.A.:
DAN S.S. 11 COCCAGLIO (BS) ITALY
TEL. +390307721850 FAX +390307240612 E-MAIL dantech@deantoni.it

period of time. This produces a dry, abrasive-coated wheel with a flexible surface. The buffing wheels on which greaseless compounds can be applied are sewn muslin buffs, pocketed buffs, full disk loose buffs, and string wheels. The coarser the abrasive particle, the duller the satin finish; the finer the abrasive particle, the brighter will be the satin finish.

BAR COMPOUNDS

Bar compounds contain two types of ingredients; binder and abrasive. The binder can consist of one or more materials taken from animal or vegetable fats as well as petroleum and similarly derived products. Animal fats are such materials as fatty acids, tallows, and glycerides. Waxes can be from vegetable, insect, or petroleum-based products. Petroleum-based or vegetable-based oils also may be used. The animal and vegetable materials are more saponifiable and will produce a water-soluble soap when combined with alkali. Petroleum, mineral oils and waxes are unsaponifiable and, therefore, might create subsequent cleaning problems.

Each ingredient is added to the binder to transmit a specific effect to the bar compound such as lubricity, degree of hardness, or improved adherence to a buffing wheel. A binder also controls the amount of frictional heat that can be developed on a surface. This is called slip. There is a wide range of abrasives used in buffing compounds, a few of which will be described.

BUFFING ABRASIVES

Aluminum Oxide and Other Powders

Aluminum oxide powders, fused and unfused, are the abrasives most commonly used in the buffing of hard metals. Chromium oxide is used to achieve the highest reflectivity (color) on stainless steel, chromium, and nickel plate. To achieve a high reflectivity (color) on brass, gold, copper, and silver, iron oxide is generally used. Aluminum oxide is chemically represented as Al_2O_3.

The unfused aluminum oxide is white in color. This is manufactured from bauxite or hydrated aluminum oxide by heating it at elevated temperatures. This heating process, called calcination, gives the abrasive the common name calcinated alumina. The higher the calcination temperature, the more water of hydration is driven off and the harder the crystalline material becomes.

When the calcinated temperature is about 950°C, the product produced is a soft alumina having a porous structure. This type of abrasive is used for luster or color buffing. When the calcined temperature is about 1,250°C, a harder alumina is produced. This type of abrasive is used for cutting. Soft aluminas are used to produce luster or a higher reflectivity on all metals, both ferrous and nonferrous. The harder aluminas will cut and remove more metal from the surface of castings or extrusions of aluminum, brass, and other metals.

When alumina is heated to 1,850°C, fused aluminum oxide (Al_2O_3) is produced. This material is made in an electric furnace at approximately 2,000°C. Bauxite, when mixed with alumina and other oxide materials, produces a specific crystalline structure whose hardness can be varied to meet specified physical properties. This fused mass is then cooled and crushed. In the crushing process, the material is ground, screened to the appropriate size, treated magnetically, and acid washed. It is then rescreened to its final classification (grit sizing).

The difference between fused aluminum oxide and calcined alumina is that the fused oxide is of a crystalline structure that is much harder than that of the calcined alumina. Fused aluminum oxide is used mainly on abrasive belts or setup wheels for polishing. As for buffing,


BUFFING WHEELS
BUFFING WHEELS
GripFan
FLEX SHAFT
NYLOX BRUSH
NYLOX BRUSH

Table I. Hardness of Abrasive Materials

Abrasive Type	*Chemical Symbol*	*Mohs' Scale*
Aluminum oxide (fused)	Al_2O_3	8–9+
Aluminum oxide (calcined)	Al_2O_3	8–9+
Tripoli-silica	SiO_2	7
Silicon carbide	SiC	9.6
Iron oxide (red rouge)	Fe_2O_3	6
Chrome oxide (green rouge)	Cr_2O_3	8–9

fused aluminum oxide is used for cutting down ferrous metals. The abrasive sizing is generally from 60 grit to –325 grit for buffing compounds.

Tripoli

Tripoli is considered to be microcrystalline silica, which is made naturally. It is highly suitable for buffing of aluminum, brass, copper, and zinc die cast or other white metals. Tripoli and silica can be used as a cutting abrasive or a so-called cut-and-color abrasive for nonferrous metals. Tripoli should not be classified as an amorphous silica, but it is microcrystalline in nature. Crystalline silica may cause delayed lung injury for people when exposed to it over a long period. Users of products containing these abrasives should be aware of this possibility and should wear a mask and work in a ventilated area.

Silicon Carbide

Silicon carbide (SiC) is of a crystalline structure that is harder than fused aluminum oxide. It is formed by mixing coke and silica in an electric furnace at approximately 1,900 to 2,400°C. The material is cooled, ground, and sifted to the required grit size similar to the processing of fused aluminum oxide. The crystalline structure of SiC is a hexagonal.

Red Rouge

The chemical formula for rouge is Fe_2O_3; it is also called jeweler's rouge. Its purity is 99% ferric oxide. The crystalline structure of ferric oxide is spherical. Rouge is used mainly on precious metals to give an exceptional high luster.

Green Rouge

The chemical formula for chromium green oxide is Cr_2O_3. The hardness of chromium oxide is 9 Mohs as opposed to iron oxide, which is 6 Mohs, and is used to produce an exceptional luster or color on ferrous as well as nonferrous metals.

These abrasives mentioned represent a small percentage of material available to give a specific finish required on a particular substrate. See Table I for typical hardness values.

Although the wheel speeds for buffing with grease bars will vary greatly from job to job and operator to operator, the figures in surface feet per minute given in Tables II and III will serve as a guide for hand buffing operations. Buffing wheel speeds for automatic operation may vary with the design of the machine and the contact of the work to the wheel. It can, therefore, be more definitely fixed without depending on the physical ability of the hand buffer to maintain the correct position and pressure against the wheel.

Table II. Wheel Speeds for Hand Buffing, sfm

	Cutting Down	*Luster Buffing*
Carbon and stainless steel	8,000–9,000	7,000–9,000
Brass	6,000–9,000	6,000–9,000
Nickel	6,000–9,000	6,000–8,000
Aluminum	6,000–9,000	6,000–7,000
Zinc and other soft metals	5,000–8,000	6,000–7,000
Chromium		7,000–8,000

LIQUID SPRAY BUFFING

Liquid spray buffing compositions have largely replaced bar buffing compositions on automatic buffing machines. Unlike the bar compound previously discussed, liquid buffing compound is a water-based product. The liquid buffing compound has three main constituents: water, binder, and abrasive. Water is used as the vehicle to transport the binder and abrasive to a buffing wheel through a spray system. This water-based liquid is an oil/water emulsion. In this emulsion the abrasive particle is suspended and could be thought of as particles coated with a binder material. The emulsifying materials act as a device to hold the oil-soluble molecules onto the water molecules.

Larger abrasive particles offer less surface area (when compared with the weight of that particle) than several smaller particles. Surface area and density play an important role in the suspension of any liquid emulsion. Stability is the ability to keep the abrasive particle in suspension. When the abrasive particles tend to fall out of suspension, their weight factor is greater than the ability of the emulsified material to maintain stability. Viscosity, therefore, plays an important role in a suspension. A totally unstable emulsion will settle out under all circumstances.

The flow characteristics of a liquid buffing compound are controlled generally by the viscosity of that compound as well as its degree of slip. The viscosity stability of any emulsion is established by its thixotropic nature, which means the viscosity becomes lighter in direct proportion to the amount of shear to which the compound is subjected.

As the degree of slip is increased, the flow characteristics of the compound will also increase in direct proportion to the resultant change in slip or the resultant change in the coefficient of friction.

The gel-type property of an emulsion is broken down by the action of the pump, thus producing viscosity changes. The changes are determined by the amount of shearing action of the pump and the length of time. This breakdown is necessary to allow the transfer of the buffing compound from the pump to the spray gun, which often requires a significant distance.

The viscosity of a liquid compound is measured under a constant set of conditions. To measure viscosity, a representative sample from a batch is needed. This sample must be in a state of equilibrium for a defined period and at a constant temperature. A viscometer is used with a specific spindle. This reading multipled by a factor will give a viscosity reading in centipoise. A deviation of 25% is normal. The control of viscosity of a compound is somewhat difficult. Variations in raw materials or the method of blending are two reasons for viscosity changes. Viscosity is an arbitrary measurement.

Liquid compounds are supplied to the spray guns by means of either air pressure feed tanks or drum pumping equipment. Air pressure is varied depending on the viscosity of the liquid compound, the length and diameter of the fluid lines feeding the spray guns, and the actual number of spray guns. With one or two spray guns close to the tank, 10 to 15 psig tank pressure may be sufficient, while 6 to 8 guns could require 40 to 45 psig tank pressure.

A drum pumping system is inserted into a steel drum. The pump then transfers the compound through a fluid line or manifold that feeds the guns. Depending on the size of the system, the drum pump is operated at 10 to 40 psig air pressure.

Table III. Production Buffing Techniques

Material to Finish	*Satin Finishing*	*Cutdown Buffing*	*Color Buffing*
Aluminum	Aluminum oxide greaseless compound light head of dry tripoli bar. Loose or ventilated buff or string wheel, 3,000 to 5,000 sfm	Tripoli bar or liquid compound. Loose or ventilated buff, 6,000 to 8,000 sfm	Rouge, silica, unfused aluminum oxide bar or liquid compound, loose or low-density ventilated buff, 6,000 to 8,000 sfm
Brass	Aluminum oxide greaseless compound. Loose or ventilated buff, string wheel 3,500 to 5,500 sfm	Tripoli bar or liquid compound. Ventilated loose or sewn buffs, 5,000 to 8,000 sfm	Rouge, silica or unfused aluminum oxide bar or liquid compound, loose or low-density ventilated buffs, 5,000 to 8,000 sfm
Hard chromium	Aluminum oxide greaseless compound. Loose buff, 5,000 to 6,500 sfm		Chromium green oxide or unfused aluminum oxide bar or liquid compound, loose or ventilated buff, 5,000 to 6,500 sfm
Chromium decorative plate	Lubricated silica greaseless compound, loose buff, 3,000 to 4,500 sfm	For burnt areas: Combination fine fused and unfused aluminum oxide bar, loose or ventilated buff, 6,500 to 8,000 sfm	Chromium green oxide, unfused aluminum oxide bar. Loose or ventilated buff, 6,500 to 8,000 sfm
Copper	Aluminum oxide greaseless compound. Loose or ventilated buff string wheel, 4,500 to 6,000	Tripoli bar or liquid compound. Loose sewn or ventilated buffs, 5,500 to 7,500 sfm	Rouge, silica, or unfused aluminum oxide bar or liquid compound, loose or low-density ventilated buff, 5,500 to 7,500 sfm
Copper plate	Aluminum oxide greaseless compound. Loose or packed buff, string wheel, 3,000 to 5,000 sfm	Tripoli bar or liquid compound. Loose or ventilated buff, 5,000 to 7,500 sfm	
Nickel and alloys	Aluminum oxide greaseless compound. Loose or ventilated buff, 5,000 to 7,500 sfm	Tripoli bar or liquid compound. Loose sewn or ventilated buff, 5,000 to 8,000 sfm	Chromium green oxide or unfused aluminum oxide bar or liquid compound, loose or ventilated buff, 5,000 to 8,000 sfm
Nickel plate decorative	Aluminum oxide greaseless compound. Loose or ventilated buffs, 4,500 to 5,500 sfm		Chromium green oxide, or unfused aluminum oxide bar or liquid compound, loose or low-density ventilated buff, 6,500 to 7,500 sfm
Steel and stainless steel	Silicon carbide or aluminum oxide greaseless compound. Loose or ventilated buff, 4,500 to 6,500 sfm	Aluminum oxide bar or liquid compound. Ventilated, sewn, sisal finger or tampico buffs, 8,000 to 10,000 sfm	Chromium green oxide and/or unfused aluminum oxide bar or liquid compound, loose or ventilated buffs, 8,000 to 10,000 sfm
Zinc	Aluminum oxide greaseless compound. Loose or ventilated buff, 5,500 to 6,500 sfm	Tripoli bar or liquid compound. Loose ventilated or sewn buffs	Silica or unfused aluminum oxide bar or liquid compound, loose or low-density ventilated buffs, 6,000 to 8,000 sfm

The spray gun is usually mounted in back of the buffing wheel so it will not interfere with the operator and is at a distance from the buffing wheel face so that complete coverage of the face of the buff is obtained with proper regulation of the spray gun. An opening in the dust collecting hood allows the compound to be sprayed from this position. Where buffing machines are totally enclosed, there are no hoods to interfere with the placement of the guns. The spray guns are actuated by air, which is released, in the case of manually operated lathes, by a foot valve that allows the buffer to keep both hands on the part being buffed. With automatic machines, solenoids allow the flow of air to operate the guns. The solenoids are connected to an electric timer where an on-time and an off-time can be set depending on the frequency of the compound needed on the buff face.

A buffing head is a series of buffing wheels put together producing a buff face. This buff face can vary in length depending on contact time needed to do a certain job function. To adequately apply buffing compound to the wheel face, spray gun movers or multiple gun set-ups are usually employed. This allows the liquid compound to be applied across the entire buff wheel face. Spray guns will generally produce a fan of 10 to 12 inches per gun.

In manual operations, the main advantage of the spray composition method is to save the operator time. He or she does not have to stop buffing to apply the cake of conventional solid composition. The operator can remain buffing and apply the liquid compound by the use of a foot peddle, hence less motion is used in applying the compound thus increasing productivity.

In the case of automatic machines, the spray equipment replaces mechanical application. Shutdown time for regulation of mechanical applicators in most cases amounts to more than 25% of the theoretical maximum production time. This is almost entirely eliminated.

The advantages of liquid spray buffing for both automatic and manual buffing procedures are as follows:

1. Optimum quantity of composition is readily controlled on the buff surface, the composition being supplied regularly rather than haphazardly. With buffing bars, an excess of composition is present when the first piece is buffed and an insufficient amount is present for the last piece of work before another application of the bar. If this were not true, the operator would handle the bar of composition more often than the work. Using the spray method, the desired amount of composition is present for each piece buffed.
2. With a deficiency of composition of buffing compound present, the buffing cloth is worn excessively. Spray compositions, eliminating this deficiency of coating, also eliminate this cause of unnecessary buff wear.
3. Solid buffing dirt is packed into the crevices of the work when an excess of buffing composition is present. The serious cleaning problem presented by this dirt is well known. As there need be no excess of composition using the spray method with properly formulated compositions, cleaning after buffing is greatly simplified.
4. Significant savings can be realized in compound consumption, because all the liquid composition brought to the lathe can be used. There are no nubbins left over.
5. Where high pressures exist between the work and the buffs, a deficiency of compositions has often resulted in such a high frictional heat that the muslin buff catches fire. The spray method eliminates this hazard by keeping the buff properly coated at all times; however, a spray composition must be selected that does not constitute a fire hazard, which would be present if a liquid composition were composed of volatile, combustible fluids.

When using bar compound on an automatic machine, wheel speeds must be maintained in the higher range to generate sufficient friction to exceed the melting point of the bar; however, much lower wheel speeds may be used when liquid compounds are used. The ability to slow down the surface feet enables more intricate parts to be buffed. The lower buffing wheel speeds with large buff faces and liquid compound allow the slowly rotating work to be

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pushed up into or "mushed" into the buff wheel. Although the amount of work per unit of time might be lowered, this is compensated by increasing the buff contact time on the work by using wide-faced buffs.

Airless spray systems provide a significant breakthrough in developing a highly efficient method of applying liquid buffing compositions for automatic and semiautomatic buffing operations. Such a system uses high fluid pressures in the range of 600 to 1,800 psi. Specially designed, air-activated drum pumps generate such high fluid pressures and deliver custom-formulated, heavy viscosity liquid buffing compounds to special automatic spray guns with tungsten carbide insert nozzles. Much like the action of a watering hose, the high fluid pressures force the heavy liquid buffing compounds through the orifice of the spray gun for controlled fracturing of the compound. This high velocity spray is capable of penetrating not only the wind barrier around a rotating buff, but has enough force behind it to impregnate the cloth buff up to a 1.5-in. depth, depending upon the construction and speed of the buff. Overspray, so common to regular external atomizing spray systems, is practically eliminated.

Deep saturation of the buff with the compounds provides more consistent and uniform finishes, with reduced compound consumption up to 35%. Extended buff life also reduces changeover downtime. Operating costs are further reduced with lower compressed air consumption because airless spray guns do not require atomizing air to apply the compounds.

Airless spray buffing systems presently in operation limit applications to custom-formulated, heavy viscosity liquid buffing compounds containing tripolis and unfused aluminum oxides. Properly designed drum pumping systems must be used. High pressure fluid hose and fittings are also necessary. The high fluid pressures generated in airless spray buffing systems make it necessary to exercise certain precautions. When adjusting the spray guns, operators must be careful not to allow the force of the spray to come in contact with exposed skin, since the force of compound is strong enough to break the skin.

Liquid abrasive compounds offer so many recognized advantages that their use is now accepted by the finishing industry as standard procedure for high production buffing.

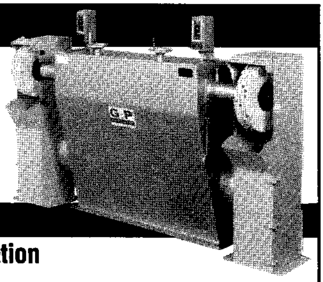
POLISHING AND BUFFING OF PLASTICS

Due to the dies used to mold plastic, little buffing or polishing is required. Some do require removal of flash, parting lines, sprue, projections, gates, and imperfections from areas that may need further surface finishing. Plastics cut and machined generally need abrasive finishing to bring back their original luster using belt polishing and buffing. Plastic compounds are formulated to remove large amounts of stock without generating too much frictional heat between the part and the wheel (preventing crazing of the plastic). Some buffing compounds contain built-in antistatic materials so that the buffed surface resists the adhesion of airborne lint. When buffing plastic, the material becomes statically charged.

On surfaces of plastic laminates, where fibrous fillers are completely covered with either a thermoplastic or thermosetting plastic, polishing and buffing recommendations are the same as those given for the particular plastic binder involved.

Heavy flash removal, sprues, flat surfacing, and beveling on thermosetting and thermoplastic articles are usually done with wet belt sanding. Special waterproof abrasive belts are most generally used. The abrasive grit size is determined by the amount of flash that must be removed.

For flexible polishing of thermosetting plastic articles, greaseless compound provides a dry and resilient abrading face for removal of light or residual flash, imperfections in the surface, and cutting tool marks, or for smoothing out irregularities on the contours left by the belting operation. Thermoplastic articles readily distort with frictional overheating. To avoid this problem minimum work pressure against the coated buff wheel and low peripheral speeds are needed. To assure low frictional heat development, grease sticks also can be applied to the coated buffing wheel. This gives added lubrication and lowers the amount of drag, which produces the heat buildup.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BUFFING OF PLASTIC

Buffing is usually divided into cutdown and luster or color buffing. Cutdown buffing produces a semigloss finish from the dull, sanded surface resulting from belt sanding or greaseless compound operations. This semigloss finish is adequate as a final finish in some cases. Where a higher luster is required, this cutdown buffing is the intermediate operation prior to the final high luster buffing.

The most popular buffs used are full disk sewn 80/92 count cloth for cutdown and full disk loose, bias type, or ventilated 64/68 count for luster. Buffing pressure should be at a minimum and the buff speed slow to prevent "burning" the plastic. Keeping the buff well lubricated with buffing compound in the cutdown operation helps minimize the burning.

MILL AND ARCHITECTURAL FINISHES (STAINLESS STEEL)

The main concern of most fabricators of stainless steel is to remove welds and machining marks, and blend and simulate the final finish with the original mill finish or the sheet or coil stock. To refine the area of welds and machining marks, standard rough polishing procedures used are as those previously discussed. Note that the final surface finish must closely approximate the original mill finish. There are eight basic stainless steel mill finishes used in the industry by product designers and architects. Mill finish Nos. 3, 4, 6, 7, and 8 are produced mechanically using some type of abrasive media and buffing wheels. Finish Nos. 3 and 4 have proven to be the most popular among fabricators of dairy, kitchen, cafeteria, chemical equipment, and architectural and decorative structures. The simplest way to produce these blended finishes is with string wheels coated with greaseless abrasive compositions containing 80, 120, or 180 grit abrasive, operating at relatively low speeds.

Narrow, flat, or curved areas can easily be blended with a portable power tool and a string wheel up to 8 inches in face width. Medium or very wide areas are finished with a string wheel log held with two hands or by two operators. Such a polishing log is made up of string wheel sections on a desired width shaft of a sufficiently powered portable tool. The greaseless compound is applied to the rotating string wheel log and allowed to dry a few minutes. String wheel blending is then quickly accomplished in the direction of the lines of the original mill finish.

Mill finishes Nos. 6, 7, and 8 are most generally used on consumer products, although on some architectural sections they are produced for contrasting patterns.

BASIC STAINLESS STEEL SHEET FINISH DESIGNATION

The following list of stainless steel sheet finish designations includes a brief description of how each finish is obtained.

Unpolished Finish No. 1: A dull finish produced by hot rolling to specified thickness, followed by annealing and descaling.

Unpolished Finish No. 2D: A dull finish produced by cold rolling to specified thickness, followed by annealing and descaling. May also be accomplished by a final, light roll pass on dull rolls.

Unpolished Finish No. 2B: A bright finish commonly produced in the same way as No. 2D, except that the annealed and descaled sheet receives a final, light cold-roll pass on polished rolls. This is a general purpose, cold-rolled finish, and is more readily polished than the No. 1 or No. 2D finishes.

Polished Finish No. 3: An intermediate polished finish generally used where a semipolished surface is required for subsequent finishing operations following fabrication, or as a final finish with a 50- or 80-grit abrasive compound.

Polished Finish No. 4: A general purpose bright polished finish obtained with a 100 to 180 mesh abrasive, following initial grinding with coarser abrasives.

Buffed Finish No. 6: A soft satin finish having lower reflectivity than No. 4 finish. It is produced with a greaseless compound, #200 grit, top dressed with white rouge or chromium green rouge.

Buffed Finish No. 7: A highly reflective finish produced by buffing a surface that has first been refined to approximate a No. 6 finish, then buffed lightly with a white rouge without removing satin finish lines.

Buffed Finish No. 8: The most reflective finish commonly produced. It is obtained by flexible polishing with successively finer abrasive compounds, then buffing extensively with a very fine chromium green rouge bar compound.

FINISHES FOR ARCHITECTURAL ALUMINUM

Due to the different aluminum alloys, variations in final surface finish may occur. Variations may also occur by the type of buffing equipment used, type and size of the buff wheels, peripheral speed of the buff, the type of abrasive composition used and operator's technique. When using automatic equipment, the operator technique is replaced by a mechanical system controlling such variables as pressure, time cycle, conveyor speed, and contact time against the buffing wheel, resulting in a more consistent finish.

Aluminum and its alloys are soft metals with a high frictional coefficient. As previously discussed, tripoli or silica is used for a cutdown or cut-and-shine operation on aluminum. Calcined alumina compounds are used for shine on the aluminum surface.

Description of Architectural Finish Designations

Series (a) As fabricated. No buffing or polishing required.
Series (b) Medium bright soft textured satin finish.
Series (c) Bright buffed finish over soft texture satin.
Series (d) Bright buffed finish on original surface.
Series (e) Coarse directional satin finish.
Series (f) Medium directional satin finish.
Series (g) Fine directional satin finish.
Series (h) Hand-rubbed satin-type finish (small areas only).
Series (i) Brushed finish.
Series (j) Nondirectional satin finish.

General Recommendations

The following recommendations are step-by-step instructions for obtaining the designated architectural finishes.

Series (b) Finishes: Polish with a wheel coated with an abrasive and cement paste with 80 to 150 grit on sewn or ventilated buffs, lightly lubricated with special bar or liquid lubricants. Buff speed 6,000 sfm. Final polish with a wheel coated with an abrasive and cement paste with 320 grit using the same buff and same speed.

Series (c) Finishes: Polish with an abrasive and cement paste coated wheel, 320 grit on sewn or ventilated buff. Light lubrication with special bar or liquid lubricant. Bright buff with clean working tripoli bar compound or liquid tripoli buffing compound on ventilated, sewn, or loose buff. Buff speed 7,000 sfm.

Series (d) Finishes: Bright buff only over original surface as for series (c) finishes. No prior polishing required.

Series (e) Finishes: Coarse satin finish with greaseless compound of 80 grit over glue base buff sizing on a ventilated or sewn buff, or with liquid abrasive 80 grit on the same type buff. Lubricate the dried compound head with a special bar or liquid lubricant. Buff speed 6,000 sfm.

Series (f) Finishes: Medium satin finish with greaseless compound, 120 grit, over a blue base buff sizing on ventilated or sewn buffs, or with liquid abrasive 120 grit on the same type buff. Lubricate dried compound head with a special bar or liquid lubricant.

Series (g) Finishes: Fine satin finish with greaseless compound, 150 grit, on a ventilated, sewn or loose buff, or with liquid abrasive 150 grit on the same type of buff. Lubricate dried compound head with a special bar or liquid lubricant. Buff speed 6,000 sfm.

Series (h) Finishes: Hand rubbed finish, using coarse steel wool lubricated with a special liquid lubricant. Final rubbing with No. 0 steel wool.

Series (i) Finishes: Brush type finish produced with string wheels coated with greaseless compound, 80 grit. String wheel speed 6,000 sfm. Buff head may require some light lubrication with a special bar lubricant, depending on alloy of aluminum. Nylon impregnated wheels are also used for this finish.

Series (j) Finishes: Brush type finish produced with a string wheel coated with greaseless compound, 80 grit, but operated at a slow speed of 2,000 to 3,000 sfm. May also require some light lubrication with a special bar lubricant. Again, nylon impregnated wheels may also be used.

When high production satin finishing is required for series (e), (f), (g), and (i), use a liquid greaseless abrasive. Such compositions may be applied automatically with properly designed spray equipment. Light lubrication of the satin finished head, when required, is done with nonmisting, low atomizing spray equipment.

SAFETY REQUIREMENTS OF POLISHING AND BUFFING

Due to increased concern for industrial and environmental safety, state and federal authorities have drawn up guidelines for controlling industrial hazards. These guidelines protect the user as well as the environment.

Buffing processes propel dust particles, cotton lint, abrasive dust, and metallic dust into the air. Microcrystalline silica, or tripoli, which is used in buffing compounds, is a good example of such dust. According to OSHA permissible exposure limits, exposure to airborne crystalline silica shall not exceed an 8-hour time-weighted average limit as stated in 29 CFR Part 1910 1000 Table Z-3 for Mineral Dusts, specifically "Silica: Crystalline: Quartz (respirable)." The threshold limit value and biological exposure indices for the 1987–1988 American Conference of Governmental Industrial Hygienists is 0.1 mg/m^3 (respirable dust).

Excessive inhalation of dust may result in respiratory disease including silicosis, pneumoconiosis, and pulmonary fibrosis.

The International Agency for Research on Cancer (IARC) has evaluated *Monographs on the Evaluation of the Carcinogenicity Risk of Chemicals to Humans, Silica and Some Silicates* (1987, Volume 42), that there is "*sufficient evidence* for carcinogenicity of crystalline silica to experimental animals" and "*limited evidence*" with respect to humans.

A conventional particulate respiratory protector is required based on considerations of airborne concentrations and duration of exposure. Refer to the most recent standards of the American National Standard Institute (ANSI Z.88.2), the Occupational Safety and Health Administration (OSHA) (29 CFR Part 1910 134), and the Mine Safety and Health Administration (MSHA) (30 CFR Part 56). The use of adequate ventilation and dust collection is also required.

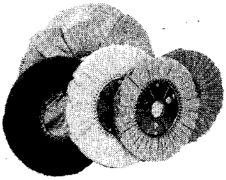
Grinding, polishing, or buffing operations that generate airborne contaminants in excess of exposure limits into the breathing zones of employees should be hooded and exhausted as necessary to maintain legal exposure limits. A hood used for the control of contaminants from a grinding, polishing, or buffing operation should be connected to an exhaust system that draws air through the hood to capture air contaminated by the operation and to convey the contaminated air through the exhaust system.

Where large quantities of exhaust air cause negative pressures that reduce the effectiveness of process exhaust systems or cause a carbon monoxide hazard due to back-drafting of flues of heating devices, provisions shall be made to supply clean make-up air to replace the exhausted air. The make-up air supply, where necessary, should be adequate to provide for the combined exhaust flows of all exhaust ventilation systems, process systems, and combustion processes in the workplace without restricting the performance of any hood, system, or flue.

Dust collection equipment is available in numerous designs utilizing a number of principles and featuring wide variation in effectiveness, first cost, operating and maintenance costs, space, arrangement, and materials of construction. Consultation with the equipment manufacturer is the recommended procedure in selecting a collector for any problem where extensive previous plant experience on the specific dust problem is not available. Factors influencing equipment selection include:

1. Concentration and particle size of contaminant
2. Degree of collection required
3. Characteristics of air or gas stream
4. Characteristics of contaminant
5. Method of disposal

There are many other aspects of buffing and polishing than these briefly discussed here. Though this very important contributor to the metal-finishing industry is more of an art than a science, basic engineering principles can be applied to this operation. With the proper melding of buff and compound, applied in a controlled fashion, optimum finish and maximum economy can be achieved.



BUFFING WHEELS AND EQUIPMENT

by David J. Sax

Stan Sax Corp., Detroit

Three elements to a successful buffing operation are the buff wheel, the buffing compound, and the buffing machine. It is necessary to understand all of these elements and how they interact to achieve desired quality, productivity, cleanability, corrosion resistance, reject elimination, and overall cost-effectiveness.

WHAT IS BUFFING?

Buffing is a mechanical technique used to bring a workpiece to final finish. It also can be used to prepare the surface of a machined, extruded, or die-cast part for plating, painting, or other surface treatment. The objective is to generate a smooth surface, free of lines and other surface defects.

Buffing is not a process for removing a lot of metal. Deep lines and other more severe surface defects should be removed before buffing by polishing with a polishing wheel or abrasive belt.

Buffing usually involves one, two, or three steps: cut buffing, intermediate cut, and color buffing. These operations normally are performed by what is referred to as either "area" buffing or "mush" buffing.

Cut Buffing

A harder buff wheel and, generally, a more abrasive buffing compound, are used to start the buffing process. In cut buffing, the buff wheel and workpiece are usually rotated in opposite directions to remove polishing lines, forming marks, scratches, and other flaws.

Color Buffing

When a mirror finish is specified, a color buff step may be required. Color buffing may be performed with a softer buff wheel and less aggressive abrasive compounds. In color buffing, the buff wheel and workpiece are usually rotated in the same direction. This enhances the cut buff surface and brings out the maximum luster of the product.

Area Buffing

For localized finishing, narrow buffing wheels, positioned tangentially to the workpiece, are used. This is often is referred to as "area buffing."

Mush Buffing

To finish larger parts or parts having several surface elevations, mush buffing may be used. This involves the use of one or more wide buff wheels. In mush buffing, a part is rotated or cammed through the buffing wheel. This technique is also used to finish multiple products simultaneously.

BUFFING COMPOUNDS

Buffing compounds are the abrasive agents that remove minor surface defects during the buffing phase of the finishing cycle. Buffing compounds are available in paste or solid form. There are thousands of products from which to choose. The prime consideration in selecting a buffing compound is the substrate being buffed and the surface to be provided.

Nonferrous products made of copper, nickel, chromium, zinc, brass, aluminum, etc., frequently are buffed with compounds containing silica (generally amorphous, often "tripoli"). "Tripoli" is found in a small area of Oklahoma and is shipped all over the world. Steel products are normally buffed with compounds of fused aluminum oxide, which is available in DCF collector fines and as graded aluminum oxide in a range of grit designations.

Special abrasives are available for other purposes. For example, chromium oxide is widely used to give stainless steel, chromium- and nickel-plated products high reflectivity. Iron oxides are used to color buff gold, silver, copper, and brass. Lime-based buffing compounds are used to generate mirror finishes on nickel products.

Skilled buffing engineers can help manufacturers select the optimum equipment, buffing compounds, wheels, and buffing techniques. Cleaners and cleaning processes must be matched to the soil to be removed.

BUFFING WHEELS

Fabrics used in buffing are designated by thread count and fabric weight. Count is measured by threads per inch; weight by the number of linear yards per pound of 40-inch-wide fabric. Heavier materials have fewer yards per pound. Lower thread count and lighter weight materials are used for softer metals, plastics, and final luster. More closely woven, heavier, and stiffer materials are used on harder metals for greater cut and surface defect removal. Stiffness is a result of heavier weight, higher thread count fabrics, more material, specialized treatments, sewing, and overall buff design.

Buff wheel construction determines the action of the buff by making it harder or softer, usually by varying convolutions of the face of the wheel. This influences aggressiveness. Part configuration dictates buff design, construction, thread count, etc.

Conventional buffs employ a circular disk of cloth cut from sheeting and sewn into a number of plies. For example, some materials require from 18 to 20 plies to make a ¼-in.-thick section. Multiple sections are assembled on a spindle to build the required face width. The density of these types of buffs is also controlled by spacers that separate the plies of fabric or adjacent faces from one another.

Industry standards for the inside diameter of airway-type buff wheels are 3, 5, 7, and 9 in. As a rule, productivity and buff wheel life increase as outside diameter increases and thread count and material content increases. Larger buffs and higher shaft rotation speeds also increase productivity and buff life.

The choice of buff center size depends on how far the buff material can be worn before the surface speed reduces to a point of inefficiency, or flexibility declines to a point where contours cannot be followed. Airway buff flexibility decreases with use as wear progresses closer to the steel center. Most airway buffs are designed with as much material at the inside diameter as the outside diameter.

Flanges

Buffing wheels require flanges for safe operation. Flanges must be sized for the specific inside diameter of each buffing wheel. It is important for all buffs that the flange be designed with sufficient strength to withstand the tremendous forces and pressures exerted in buffing. If buffs are not well designed and fabricated, centrifugal forces at higher speeds and the shock from operations can cause failure of clinching teeth, breakage of rings, and breakdown of buff sections.

Table I. Commonly Used Buff Fabrics

Warp (Lengthwise)	*Filler (Crosswise)*	*Cloth Weight (Linear yd/lb of 40-in.-wide material)*
60	60	3.15
80	80	3.15
86	80	2.50 (soft)
86	80	2.50 (firm)
86	80	2.50 (yellow treated at mill)

MUSLIN BUFFS

The most commonly used fabrics for buffs are cotton muslins. As previously noted, fabrics are designated by thread count (e.g., 60/60, 80/80, 86/80). These designations refer to the threads per inch in the warp and fill, respectively. Fabric weights typically run from 2.5 to 3.5 yd/lb. (Table I).

OTHER BUFF MATERIALS

Flannels

Domet flannel (with nap on both sides) and Canton flannel (nap on one side and twill on the other side) in various weights are used where other fabrics fail to produce a high enough luster. Coloring of jewelry products is a typical application for such buff materials.

Sisal

Sisal is a natural hemp fiber used for fast-cut buffing of steel and stainless steel. It is a coarse fiber twisted into strand groups and frequently woven into a fabric. It has a much lower thread count than cotton muslin, sometimes five by seven per inch, and offers the advantages of greater surface defect removal. Combination sisal/cloth buffs are effective designs (Fig. 1). The sisal plies frequently are cloth covered to omit the tendency of the sisal to cut the cotton threads of adjacent cloth plies. Alternating cloth and sisal improves compound retention, reduces unravelling, and moderates cut. Kraft paper alternated with sisal also has applications.

Other Natural Materials

Occasionally, other materials are used to form buffs. For example, woven wool buffs are used on plastics, soft metals, and sterling silver. Sheepskin buffs are used to avoid surface drag or smear when buffing metals that contain lead. Russet (bark-tanned) sheepskin is used for cut. White alum (alum-tanned) sheepskin is used for color buffing.

Pieced Buffs

Pieced buffs are less expensive because they are made of lower-cost materials. The buffs are made of colored segments, unbleached segments and occasionally bleached material.

Combination Buffs

Often different materials are combined, especially sisal with cloth, and occasionally paper as well as cloths of different specifications.

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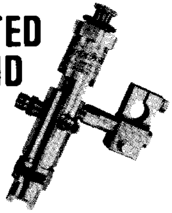

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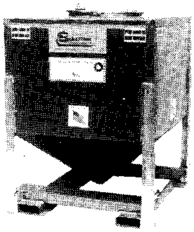

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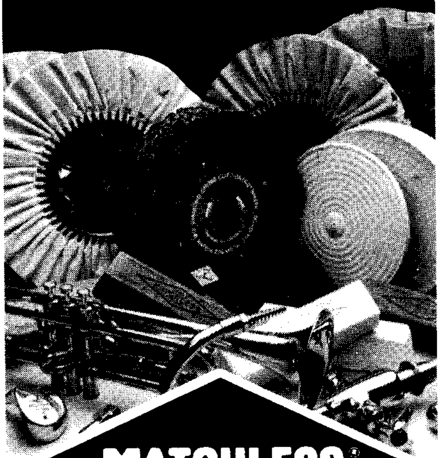

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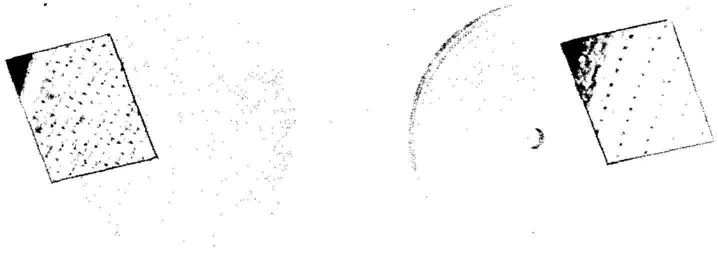
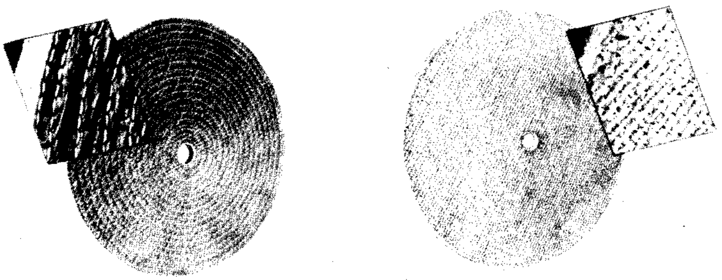


ALL SISAL

SISAL WITH CLOTH



SISAL WITH PAPER

TREATED SISAL

Fig. 1. Sisal buffs.

Synthetic Fibers

Unwoven nylon and other synthetics fibers, because of their water resistance, may be used wet or dry or with wax or grease lubricants. Buffs made of synthetics are usually operated at slow speeds, typically 2,500 sfpm, to prevent melting and streaking surfaces.

BUFF TREATMENTS

Treatments may be applied to fabrics (mill treatment) or to the buff after assembly (dip treatment). Buff fabrics are frequently hardened and stiffened to promote faster cutting, softened for additional flexibility to conform to contours, strengthened for longer buff life, or lubricated to prevent burning. Buff fabrics may also be treated to provide improved adhesion of buffing compound, to abrade for heavier cut, or to flameproof and make fire resistant. Treatments must be applied evenly and uniformly to avoid creating hard spots that cause uneven buffing. The treatment must not deteriorate with buff age. Unsuccessful treatments weaken the cloth and decrease buff life.

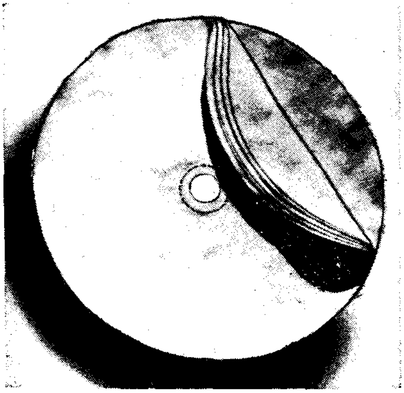


Fig. 2. Full disk buff.

CONVENTIONAL, FULL-DISK BUFF DESIGNS

Unsewn Buffs

Conventional, full-disk buffs are made with die-cut cloth disks. Unsewn, conventional full-disk buffs may be used for luster (Fig. 2). Loose disks are turned to allow the threads of the material to lie in different directions. This results in more even wear, avoiding a square shape after being put into use. One disadvantage of this conventional design is that the fabric can fray or ravel. When held against a wheel rake, a cloud of threads may fly off. This shortens buff life, increases compound consumption, and adversely affects finish. Also available are solid bias sisal buffs, with every other layer being cloth, and rebuilt buffs made from reclaimed material.

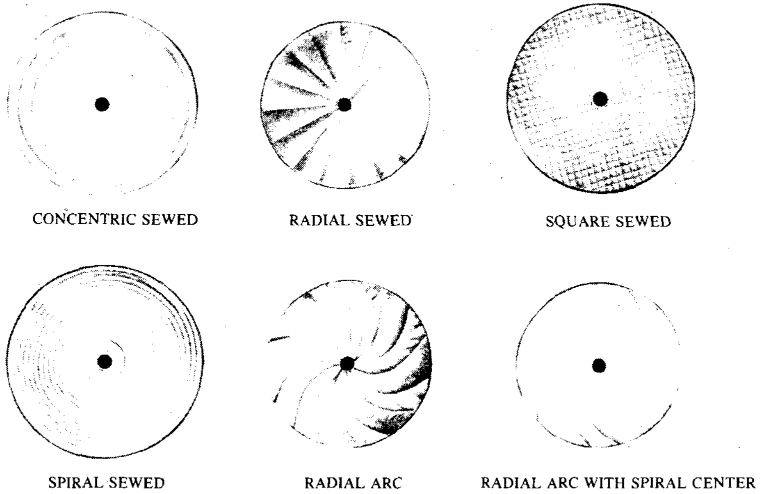
Conventional Sewn Buffs

Conventional, full-disk buffs for heavier buffing (cut) are sewn in various ways (Fig. 3). Closer sewing is specified for cutting harder metals and for removing deep imperfections.

Concentric sewing causes a buff section to become harder as it wears closer to the sewing and softer after wear causes the sewing to break through. Spiral sewing results in more uniform density. Square sewing produces pockets that help the buff wheel to retain more buffing compound. Radial sewing, sometimes called sunray sewing, and radial arc sewing provide other variations. Tangent, parallel, ripple, zigzag, cantilever, and petal sewing are used for similar reasons. Special sewing, other than spiral, which is done on automatic machines, involves more labor in the buff manufacturing process, thus increasing the price per buff.

Folded or Pleated Buffs

Folded buffs consist of circles of cloth folded twice to form a quarter circle, resulting in a "regular-pocket" buff (18 ply), or, for more cut, three times, to form eighths of a circle to constitute a denser "superpocket" (34 ply). The segments are laid down to form a circle, with each segment overlapping the previous segment. They are sewn around the arbor hole and partway to the periphery. The folds form pockets that hold compound and flex sufficiently for contour-following capacity. Folded buffs share three design deficiencies: lack of center ventilation, a tendency to fray, and waste of material in the unused center.


CONCENTRIC SEWED

RADIAL SEWED

SQUARE SEWED

SPIRAL SEWED

RADIAL ARC

RADIAL ARC WITH SPIRAL CENTER

Fig. 3. Sewn buffs.

Pleated Buff

Airway buff cloth may be accordion pleated to present more angles of material to the surface of the product to be finished. Pleating results in more cloth angles to reduce streaking and improve coloring characteristics. Better cutting is also achieved in some applications.

Packed Buffs

Buffs may be packed with spacers consisting of cloth or paper inserted between the larger diameter plies. The same spacer principle is used between buff sections. Both measures result in a softer wheel face. The packed buff construction is effective in contour buffing applications.

A version of the packed buff, for threaded, tapered spindles (2–12-in. diameter), is used in the jewelry industry. The center is hardened, usually with shellac. The sides of the buff may be reinforced by leather disks.

Pieced Buffs

Pieced buffs may be used in place of sewn full-disk buffs. They are made from remnants of cloth left over in the manufacture of other textile products. Such buffs require one of the types of sewing used for full disks in order to stay together in use. The chief virtue of pieced buffs is their higher value owing to the lower cost of materials. They usually are sold by the pound (see Table II).

BIAS-TYPE BUFF WHEELS

Bias buffs are more frequently used than conventional forms. They combine flexibility and cutting power. Bias buffs are cool running and resist burning. They are naturally ventilated. Side openings in flanges, center plates, and tabs, resulting in spacing between

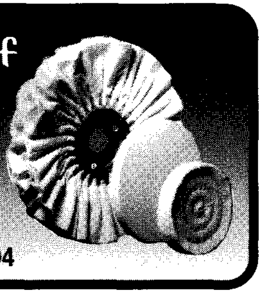


Table II. Approximate Weight Table for Spiral Sewed Pieced Buffs

	REGULAR Approx. 1/4 in. Thick		*HEAVY Approx. 5/16 in. Thick*		*EXTRA HEAVY Approx. 3/8 in. Thick*	
Diameter (in.)	*Lbs. Per 100 Sections*	*Sections Per 100 Lbs.*	*Lbs. Per 100 Sections*	*Sections Per 100 Lbs.*	*Lbs. Per 100 Sections*	*Sections Per 100 Lbs.*
4	7.4	1351	8.2	1220	11.1	900
5	11.5	870	12.8	781	17.3	578
6	16.6	602	18.4	543	24.9	401
7	22.1	452	25.0	400	33.0	303
8	29.4	340	32.7	306	44.1	227
9	36.5	274	41.3	242	54.8	182
10	46.0	217	51.0	196	69.0	145
11	55.6	180	61.7	162	83.4	119
12	66.3	151	73.5	136	99.5	100
13	77.7	129	86.2	116	116.6	86
14	90.2	111	100.0	100	135.3	74
15	103.5	97	114.8	87	155.3	64
16	117.7	85	130.6	77	176.6	57
17	132.9	76	147.4	68	199.4	50
18	149.0	67	165.3	60	223.5	45
19	166.1	60	184.2	51	249.0	40
20	184.0	54	204.1	49	276.0	36
21	202.9	49	225.0	44	304.4	33
22	222.6	45	246.9	40	333.9	29
23	243.4	41	269.9	37	365.1	27
24	265.2	38	294.1	34	397.8	25

sections, enhance their cool-running characteristics. By using material cut on the bias, the threads form an "X" at the periphery of the buff. Threads are held at a 45° angle by cross-threads. This minimizes fraying and raveling (Fig. 4).

Strips of bias-cut fabric are sewn into continuous rolls. After the rolls are cut to proper length, they are wrapped around a hub or core. They are then pulled to the desired inside diameter within the channel, usually by means of steel blades in an "Iris" machine. Straight-wound material wrapped around an oversized wheel results in a convoluted or "puckered" face; thus, the term "puckered" buff.

The "puckered" face design of bias buffs tends to break up lines left in the surface of a product from previous operations. Increasing the size of the drums varies the amount of pucker in the face. The bias buff can be adapted to various contoured parts and degrees of cutting and coloring. An advantage of the "Iris"-made buff is the elimination of material beyond the inside diameter to the arbor hole. Thus, more of the cloth is available for use.

Ventilated Bias Buffs

Although the puckered characteristic of bias buffs results in cooler running, some operating conditions require additional cooling. Steel centers with holes and ridges are designed to collect and divert more air. The air cools the buff and the workpiece surface. Clinch rings permit use of reusable metal inserts for substantial savings (Fig. 5).

PUCKERED BUFFS

Puckered buffs are rated by numbers. Higher numbers indicate greater cloth content, buff density, and face convolutions (Fig. 6). Higher densities and closer convolutions increase cutting and reduce streaking.

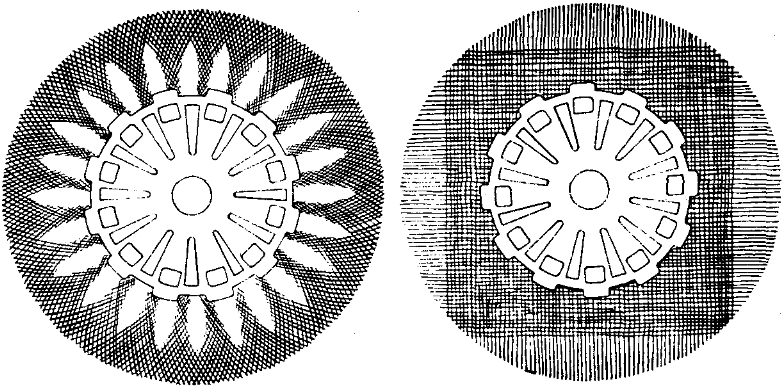


Fig. 4. Bias buff (left) versus conventional buff (right). Thread configurations of bias buffs alternate warp and filler threads. Biasing provides design efficiency by exposing all thread ends to the surface being buffed, reducing fraying of the fabric.

Open-Face Cloth Buffs

The open-face buff prevents loading, packing, clogging, and ridging during finishing operations. The plies are configured differently from the closed-face design. Buff material is wound singly or in groups of two, three, four, or more plies. Open-face buffs may be "straight wound" or "spiral wound" for a corkscrew or cross-cutting action that further minimizes streaking. Buff density varies with the number of plies, the amount of cloth, thread count, fabric weight, and treatment of the cloth. Buff pressure, speed, angle to the part, cloth strength, compound absorption ability, ventilation, and cloth flexibility are varied with buff design.

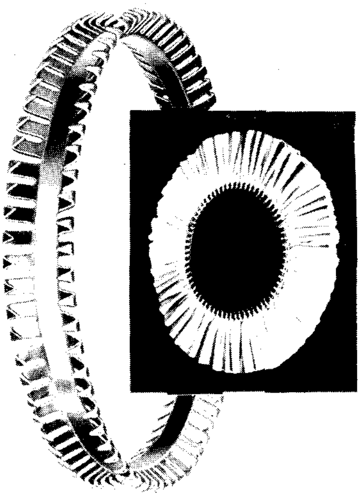


Fig. 5. Steel clinch ring (left) and steel clinch ring buff with open center (right). Buffs that are constructed by the clinch ring or "Iris" machine method have superior ventilation and cloth biasing, and optimal material utilization.

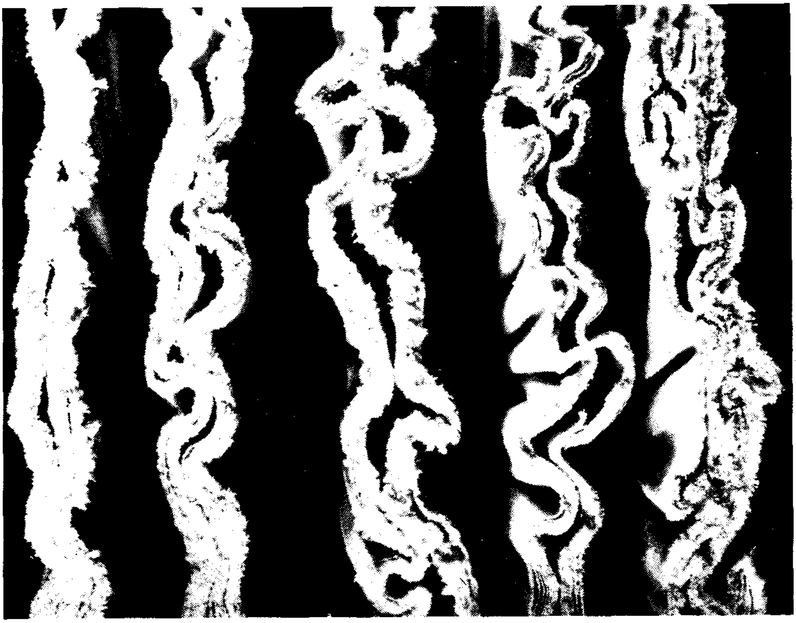


Fig. 6. Cloth bias buffs in order of increased density from closed face (left to right: 0, 2, 4, 6) to open face (far right) design.

Bias Sisal Buffs

"Iris" equipment used to gather cloth buffs is adapted to sisal and other materials (Figs. 7–10). Some bias sisal buffs are tapered (wider at the outside than the inside diameter). This reduces gaps between hard sections that could cause streaking. The tapered bias sisal buff is a long-life, cool-running buff for steel and stainless steel. Hard bias sisal buffs also are used in place of some belting operations, as well as in deburring and brushing.

Open-Cloth Bias Sisal Buff

The open cloth bias sisal (OCBS) buff is used on contoured steel and stainless steel parts (Fig. 9). It consists of woven sisal and cloth, four plies of each (eight plies total), bound together by concentric sewing before Iris gathering. The buff is manufactured in endless strips, cut to length, rolled around split drums, and gathered into clinch rings by the "Iris" machine. A variation of the open-cloth bias sisal buff is the open double-cloth bias sisal (ODCBS) buff. This design consists of two layers of cloth sewn together with one layer of sisal to make a 12-ply buff of eight plies of cloth and four plies of sisal.

Spoke Unit, or Finger Buff

Spoke unit or finger-type buffs combine great cutting power with the capacity to flex and accommodate contours and allow better workpiece coverage with fewer buffing heads. Spoke

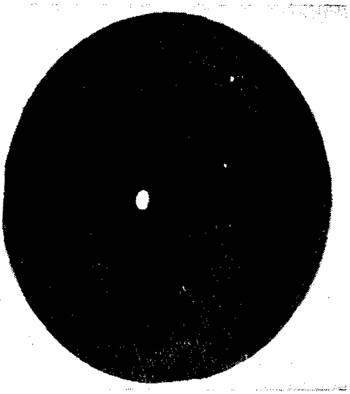


Fig. 7. Conventional sisal buff.

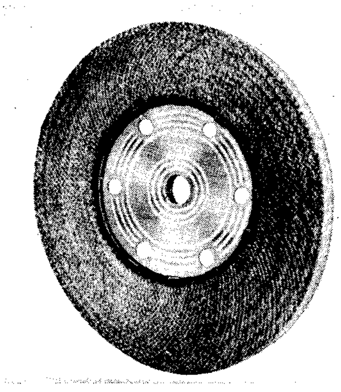


Fig. 8. Bias sisal buff.

unit or finger-type buffs are made from materials that include soft cloth, stiff cloth, sisal, and coated abrasives. The material is manufactured into units, or fingers, sewn into endless belts, cut to length, wrapped around split drums, and gathered by an "Iris" machine into steel teeth. The spoke unit or finger sisal buff is usually made with woven sisal interlaced with 86/80 cloth. Acid or rope sisal is sometimes used. The cloth may be mill or dip treated (Fig. 10).

The spoke or unit bias buff runs cooler than standard bias buffs and has a knee-action flexibility that gives superior contour-following ability. The width and number of the individual units is varied within limits. The range of buff density, or hardness, is varied by choice of materials, treatments, (buff center size) plies, and type of radial stitching. Some complex products are best finished with this type of buff.

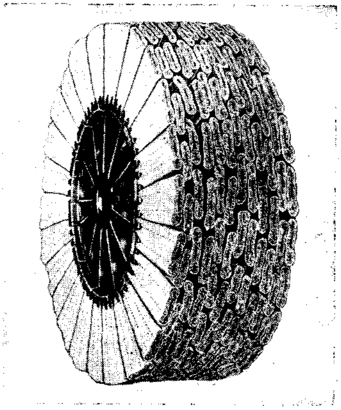


Fig. 9. Open cloth sisal buff.

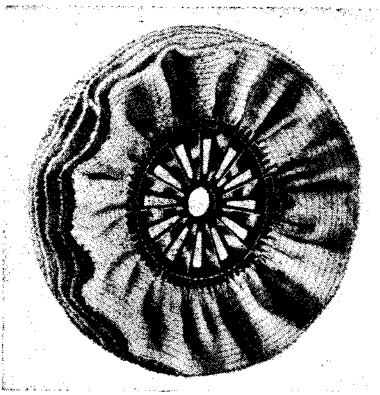


Fig. 10. Spoke unit or finger sisal buff.

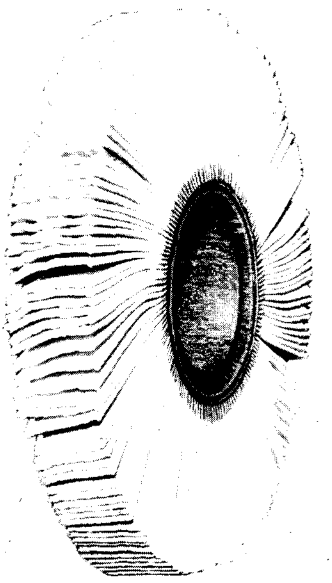


Fig. 11. Flap buff.

FLAP BUFFS

The flap buff (Fig. 11) utilizes separate flap units placed at right angles to the direction of rotation of the wheel. Each flap supports the other to produce a smooth running wheel. Flap wheels were originally designed for bumper polishing and buffing operations. Flaps are made of coated abrasives, sisal, cloth and combinations thereof.

POLISHING WHEELS

Polishing wheels are usually made of conventional cloth buff sections glued or cemented together. Canvas disks are cemented to the sides to protect the sewing. Glue or cement is applied to the face. Faces are struck with a pipe at angles and cross-angles to form a uniform crisscross of cracks on the polishing surface and provide sufficient resiliency to allow the wheel to make better contact with a workpiece.

Buff sections used to make polishing wheels are generally spiral sewn and made of various types of cloth, sisal, canvas, or sheepskin. Solid, one-piece wool felt, and bull neck and walrus hide are occasionally used.

Conventional straight buff sections that are glued together may cause streaking during polishing. An alternative involves inserting pie-shaped segments or other spacers between the buff sections to result in a "nonridge" polishing wheel that eliminates streaking. Various abrasive and adhesive combinations are used to grind, polish, and satin finish. These include liquid, graded aluminum oxide abrasives, greaseless compounds and burring bar compositions.

BUFFING EQUIPMENT

Significant improvements have been made in buff wheels and buffing compounds to provide consistent and predictable performance. This has helped manufacturers of automated buffing machines to develop automated equipment for low- as well as high-volume requirements and to minimize labor and overhead in the finishing operation.

MACHINE DESIGN

Mechanical buffing systems have a motor-driven shaft to which the buff wheel is applied. In addition, most machines will have a positioning mechanism, a finishing lathe, and workpiece-specific fixtures.

Positioning Mechanism

Automated buffing machines orient parts against the media by mechanical methods to duplicate or replace human motions. They rotate, oscillate, tilt, and index the wheel and/or the workpiece.

Finishing Lathe

The finishing lathe is a device located in relation to the positioning mechanism. It allows a buff wheel to contact one of more surfaces of the workpiece at predetermined locations.

Fixturing

The workpiece fixture or tooling is used to position a part during the buffing cycle. Buffing machines can incorporate single or multiple fixtures. Fixtures can also be designed to automatically reorient a workpiece during the buffing cycle. Buffing fixtures are unique to each part being processed, although some may be adapted to an assortment of similarly shaped parts. The design of fixtures is extremely important. Unless a part can be fixtured properly at a reasonable cost, the economical utilization of finishing equipment cannot be justified.

TYPES OF BUFFING MACHINES

Buffing machines fall within three broad categories: manual, semiautomatic, and fully automated.

Manual Machines

Manual buffing machines are used in low-volume applications and applications involving the buffing of extremely complex workpieces. Manual machines, when used in conjunction with the proper buff wheel and buffing compound, can be manipulated.

Semiautomatic Machines

Semiautomatic buffing machines are used in lower volume applications where a single finishing operation is performed on a variety of parts. Initial investment and fixturing and operating costs are low.

Semiautomatic finishing machines can be used with a single- or double-end lathe. One operator can be employed to load, unload, and operate equipment. Semiautomatic machines hold the workpiece and present it to the buff wheel. A timed cycle controls dwell and retraction. Only one fixture is required for each machine for each type of part finished. Because the machine supports the part, operator fatigue is minimized. Various types of rotation also can be performed, depending on the type of semiautomatic machine selected.

Production of semiautomatic buffing machines depends on part configuration and the degree of finishing required. By using a double-end jack with two semiautomatics, an operator can load one machine while the other is finishing a part. This can double production without increasing labor costs.

Fully Automatic Machines

Fully automatic machines are used in high-volume applications and where multiple surfaces of a workpiece must be finished. The two most common types of automatic buffing machines are rotary automatic and straight-line machines.

Rotary Automatic Machines

Rotary machines have round tables with finishing heads located around the periphery of the table. This type of machine is typically used to finish simple, round parts requiring high production. The number of finishing heads and production determine the size of the rotary.

The table of the rotary machine can move continuously or index to start, stop, dwell, and then start again, with the length of the dwell controlled by a timer. The configuration and area of the product to be finished determine which is best. Production is higher on a continuous rotary machine because the table does not stop rotating. On an indexing rotary machine, because of the stop, dwell, and start cycle, production is lower. Parts that have surfaces that are difficult to reach and require more dwell time in certain areas may be finished on an indexing rotary machine to obtain the dwell time necessary. On each table there are rotating spindles on which the parts are fixtured for the finishing sequence. Rotary tables may have a greater number of fixtures than indexing tables, since the production and simple configuration make it more appropriate to be run on a continuous machine due to the ease of reaching all surfaces.

Straight Line Machines

There are various types of straight-line automatic finishing machines. Normally, linear workpieces are finished on straight-line machines. Straight-line machines also can be used to finish round parts if extremely high production is required. There is less limitation on workpiece size as with rotary equipment.

With straight-line automatic machines, finishing heads can be placed on both sides of the machine. In addition, various heads can be incorporated into the system for buffing and polishing. With rotary equipment, the outside periphery of a rotary table is used.

Various types of straight line machines include:

Horizontal return straight line
Narrow universal straight line
Over and under universal straight line
Reciprocating straight line
Open-center universal

The size or length of these straight-line machines can be designed and built to accommodate the desired end result; floor space is the only major limitation. Each machine normally requires only one operator for load/unload. All operations of these machines are controlled from a push-button panel located near the operator for starting, stopping, and controlling various functions.

COMPUTER NUMERICAL CONTROL BUFFING MACHINES

Buffing machine manufacturers can build equipment offering the same levels of control and flexibility available from computer numerical control (CNC) metal-cutting machines.

Separate CNC workcells can be designed to combine buffing with deburring operations within a given and limited series of process steps. It also is possible to integrate a complete sequence of manufacturing operations through a universal, plant-wide parts handling system to combine fabricating, machining, deburring, polishing, buffing, painting, plating, and packaging. Such systems have a significant impact on material handling costs, daily in-process inventory levels, direct labor costs, plant floor space requirements, safety, and overall productivity.

CNC buffing systems offer a number of significant advantages. Equipment is programmed on the shop floor for reduced setup time. Buffing cycles can be reprogrammed to accommodate changing production requirements. Production data are automatically collected to support statistical process control requirements. Most important, quality is improved because part-to-part tolerances are consistent and repeatable.

WORKPIECE HANDLING

Significant advancements have been made in materials handling technology as it relates to buffing. A broad range of application-specific options is offered. These include pick-and-place workpiece load/unload systems, "blue steel" roller conveyor systems, lift-and-carry and shuttle-type in-line part transfer systems, trunnion-type transfer tables, power-and-free conveyor systems, robotic worktables, and automated guided vehicles for transferring parts between machines.

SUPPORTING TECHNOLOGY

Buffing systems are increasingly becoming turnkey, integrated installations. In addition to the basic machine, equipment builders can offer a variety of supporting systems to ensure increased performance and improved quality.

Electronic options, beyond programmable controllers and computer numerical control systems, include the use of load torque controls, sensors, proximity switches, encoders, digital read-out devices, laser gauging, and LED programmable counters. Other supporting systems include quick-change and modular wheel assemblies, automatic tool compensation, automatic buffing compound application systems, dust collection systems, and automatic workpiece shuttle and load/unload systems.

SUMMARY

Effective buffing is accomplished through the proper selection of buffing compound, the buff wheel, and the buffing machine. In most instances, it is recommended that prototype or test parts be processed under production conditions to establish process parameters and prove production rates and quality.

SURFACE CONDITIONING ABRASIVES

by Jan Reyers

3M Co., St. Paul, Minn.

Surface conditioning, or three-dimensional abrasive media, provides a means of producing uniform finishes and is used in the intermediate operations between heavy grinding or dimensioning and final buffing, plating, or application of coatings. The media are made from three basic materials: fiber, resin, and abrasive mineral (Fig. 1). These components are oriented in a manner that allows the mineral to follow along a surface in a springlike action. One of the major advantages of this type of construction is controlled cut, the ability of an abrasive media to follow over contours, removing only surface contaminants and small amounts of the substrate material. Low-density abrasives can deburr, clean, and finish surfaces without changing the geometry of the part. Production requirements, such as rate of cut and surface roughness, can be regulated by varying the rotational speeds and pressures.

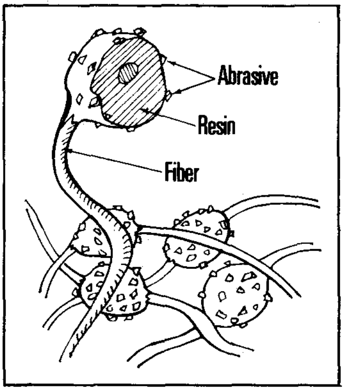


Fig. 1. Standard abrasive web.

FORMS AND GRADES

The four forms of low-density abrasive products presently available are the following:

Cleaning brushes. Abrasive web cut into disk shape, compressed together, and held in place mechanically (Fig. 2) to 18-in. diameter × 8- to 120-in. width.

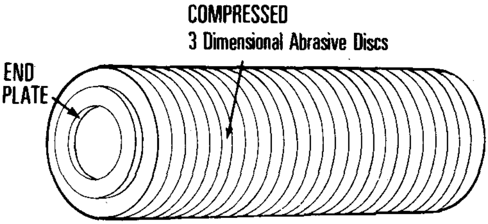


Fig. 2. Cleaning brush construction.

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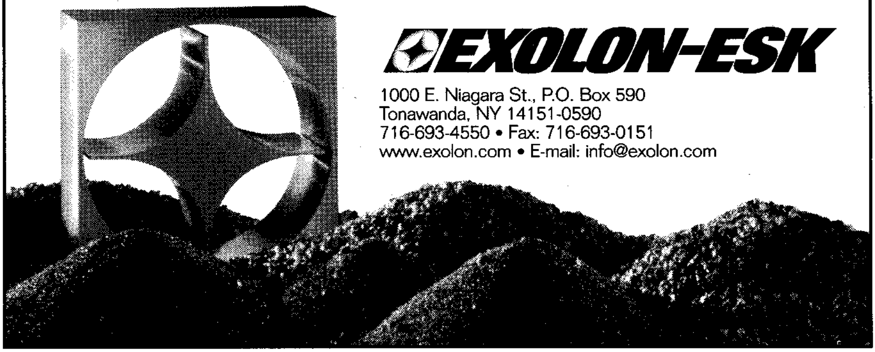

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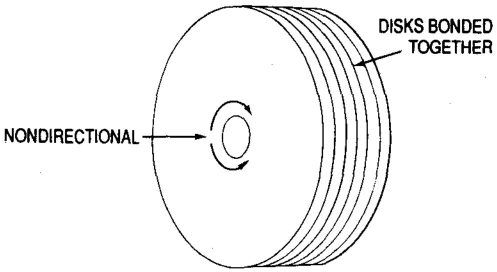


Fig. 3. Flap brush construction.

Flap brushes. Single sheets of abrasive web cut to length and adhered at a 90° angle to a steel or fiber core (Fig. 3): 6- to 18-in. diameter × ½- to 64-in. width.

Unitized wheels. Disks of abrasive web compressed together and abrasively bonded to form a solid wheel (Fig. 4): 1- to 18-in. diameter × ¼- to 1-in. width.

Convolute wheels. Abrasive web convolutely wrapped around a fiber core and adhesively bonded between layers to form a hard cutting wheel (Fig. 5): 4 to 24-in. diameter × ½ to 18-in. width.

Each of these forms is available in various grades and hardnesses that affect the amount of cut and subsequent surface roughness (rms) on a substrate (Fig. 6).

Because of their three-dimensional construction, these products are not graded by grit or mesh numbers as are conventional single-layer abrasive media such as oil wheels, setup wheels, greaseless compounds, and coated abrasives. Low-density media are available in six grades: coarse, medium, fine, very fine, superfine, and ultrafine. This method of grading in sequence for a given brush or wheel form takes the guesswork out of determining what grade should be used to prepare a surface for buffing or plating. For example, a very fine grade would be used to reduce the scratches left by a fine grade, which was used to reduce scratches remaining from a medium grade, and so forth. The surface roughness left after use of each grade can be predetermined, as illustrated in Fig. 6.

As indicated in the area of nonferrous materials, the coarser the product, the wider the microinch range, which is dependent on the type of material being worked on and its hardness.

Abrasive minerals used in low-density abrasives include aluminum oxide, silicon carbide, flint, and garnet. Varying in shape and hardness, these minerals are utilized in different products designed for specific applications. The type of material to be worked on will

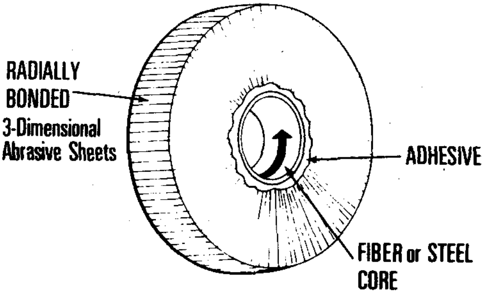
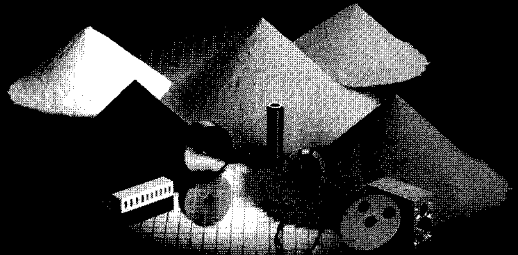
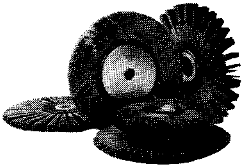
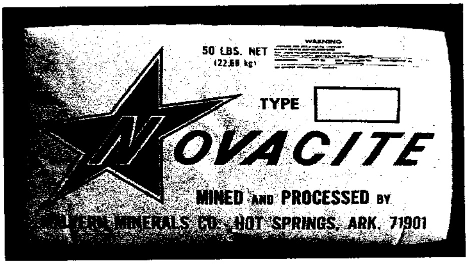


Fig. 4. Unitized wheel construction.



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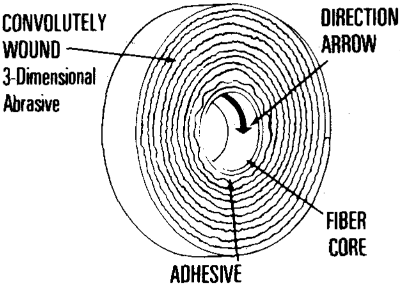


Fig. 5. Wheel construction.

dictate which mineral should be used. Aluminum oxide and silicon carbide, for example, are most commonly used on metal, glass, plastic, and rubber, whereas garnet is used primarily on wood.

The amount of abrasive web used to make up a given size and converted form determines the product's hardness. Hardness is related directly to product life, rate of cut, and finish. Densities are rated by a numbering scale, from 1 to 10. The higher the number, the harder the product. Generally, the softer products, 5 density and lower, are used for decorative finishes. These softer products conform more readily to surface contours and generate a uniform scratch finish. Typical applications are finishing nameplates, automotive and appliance trim, satin finishing of stainless steel, and a wide variety of jewelry items. They are particularly well suited for the finishing of aluminum. The lower density, nonwoven, open-type construction creates less heat at the working surface than conventional media, thereby reducing galling problems associated with finishing aluminum. The harder converted forms, 6 density and higher, are recommended for heavier stock removal, cleaning of surface contaminants, and deburring operations.

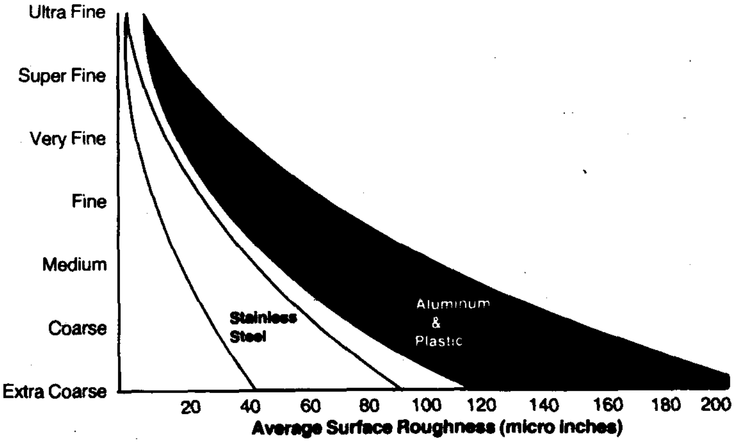


Fig. 6. Average surface roughness.

Table I. Wheel Speeds for Selected Applications, sfpm

Cleaning	2,000–5,000
Deburring	3,000–6,500
Decorative finish	500–2,500
Polishing (steel)	6,000–9,000

WHEEL SPEED AND PRESSURE

Rotational speed directly affects the rate of cut and the type of finish. The higher the surface feet per minute (sfpm), the higher the rate of cut. Of course, the maximum safe operating speed of the wheel or brush should not be exceeded. Higher speeds are used only when high rates of cut are required for polishing operations. Slower speeds will lengthen the scratch and create a more uniform, decorative finish. Some typical speeds for different applications are listed in Table I.

Work pressures for a given application depend on the selected product form and the application. Unitized and convolute wheels require higher work pressure, whereas brush forms require lower pressure and horsepower. Recommended work pressures and horsepower (hp) requirements are listed by application in Table II.

It is important that the correct pressure be used, both to generate the desired cut and finish and to obtain the most economical life from the low-density abrasive. The work pressures suggested here indicate relative amounts of work required over and above no-load or free idle of the motor. Pressure for offhand operations will be lower, usually in the 3- to 5-lb range. In practice, the optimum is obtained when the minimum pressure is used to achieve desired results. Excessive pressure can cause premature wear and does not necessarily increase the rate of cut due to the controlled cut characteristic of three-dimensional abrasives.

LUBRICANTS

Lubricants, such as soaps, waxes, tallow, water-soluble coolants, and grinding aids, can be used. Water-based coolants and grease- or oil-based lubricants can beneficially affect the life, rate of cut, and the finish produced while eliminating damage to heat-sensitive materials, such as thermoplastics and glass, by preventing heat buildup. With the use of a coolant, it is possible to increase the rate of cut of a low-density abrasive while producing a duller finish. In the case of lubricants, surface roughness can be reduced. The higher velocity lubricants produce lower surface roughness; that is, grease produces a lower rms than oil. Consequently, it is desirable to use either a coolant or a lubricant whenever possible.

SHAPING

An important feature of the low-density abrasive is that it can be readily shaped or formed to follow complex part contours. The shape will be retained throughout its usable life. One of the most effective and easiest methods used to shape wheels or brushes is to adhere a piece of 36-grit, coated abrasive to the part and hold it against the wheel until the shape is formed. Low-density abrasive wheels will retain intricate shapes without undercutting or creating flats.

Table II. Recommended Work Pressures for Various Applications

Applications	*Work Pressures (lb/working inch)*	*Horsepower (hp/working inch)*
Decorative finishing	5–10	0.1–0.15
Cleaning	10–20	0.1–0.2
Deburring	10–20	0.15–0.2
Polishing	20–40	0.5–2

BELT POLISHING

by George J. Anselment

Norton Co., Worcester, Mass.

Basically, to run a coated abrasive belt requires a power source, a tracking and tensioning device, and a method or unit to transfer the power into driving the belt. A unit, therefore, consists of (Fig. 1) the following: (A) a power source, (B) a drive wheel or contact wheel, (C) an idler for tensioning and tracking the belt, and (D) the proper coated abrasive belt.

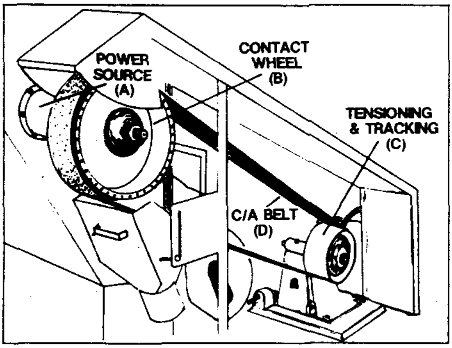


Fig. 1. Parts required to operate a coated abrasive (C/A) belt.

POWER SOURCE

In the vast majority of off-hand belt applications (in this context, "off-hand" does not imply "careless"; rather, it means with a hand-held workpiece), the amount of power consumed is directly related to the operation being performed on the workpiece and/or the operator's ability to apply pressure to the work. Naturally, an operation requiring greater amounts of stock removal will require more pressure and, hence, consume more power than will a fine-finishing operation; however, since the same equipment with slight modification can accomplish both extremes (i.e., removing excess metal or fine polishing), the horsepower (hp) requirement must be ample enough to encompass the most severe operating conditions.

Originally, the power source to drive coated abrasive belts was a converted buffing lathe, running at a fixed speed. As the industry progressed, proper belt speeds have been taken into consideration, and today a wide variety of variable-speed, single- or double-spindle "polishing jacks" are available to fit production needs.

It is seldom necessary to exceed 7½ hp for driving a single-spindle unit or to use more than 15 hp for a double-spindle jack having a common power source and utilizing an operator simultaneously on each spindle. If the spindles are powered separately, 7½ hp on each will normally suffice. Generally speaking, 1 to 2 hp per inch of belt width is sufficient; however, special application conditions may need up to 5 hp per inch of belt width. Power-assisted, work-holding devices will change horsepower requirements drastically, and 25- to 50-hp machines are not uncommon.

DRIVE WHEEL OR CONTACT WHEEL

Power is generally transmitted to the coated abrasive belt through a contact wheel, which is a multipurpose component and plays a crucial role (Table I) in stock removed per time

Table I. Contact Wheels

Surface	*Material*	*Hardness and Density*	*Purpose*	*Wheel Action*	*Comments*
Cog tooth	Rubber	70–95 Durometer	Heavy grinding	Very aggressive, retards dulling	For heavy stock removal, such as gates, risers, etc.
Standard serrated	Rubber	55–95 Durometer	Medium to heavy grinding	Excellent stock removal, not as severe as cog tooth	Not as aggressive as cog tooth, depending on land to groove ratio. Most common type
Plain face	Rubber	40–95 Durometer	Light to medium grinding	"Middle-of-the-road"-type wheel, finer surface roughness than above	For flatter surfaces or where belt might be punctured with serrations
"X"-shaped serrations	Rubber	35–70 Durometer	Polishing to light grinding	For very mild contours and light stock removal	More applicable for nonferrous parts
Flat	Compressed canvas	Available several densities from extra soft to extra hard	Polishing	Varies with density from light stock removal to fine polishes	Bench-type grinder oriented. All-around wheel
Flat	Solid sectional cloth	Available five densities, 50 to 90 plies per inch	Polishing	Uniform polishes for contoured work	Excellent for all types of finishing. May be preshaped
Flat	Buff section cloth	Variable	Contour polishing	Conformable for polishing contours and irregular shapes	Adjustable for width and density

interval, finish generated, belt life, and hence, cost of operation. Since it plays such an important part in the success or failure of off-hand metal finishing, careful selection of the contact wheel is paramount.

Contact wheels have been made of practically every workable material imaginable, ranging from cloth or building board to steel, each serving a definite purpose toward the end results. Today, commercially available contact wheels are usually made from one of three materials: (1) rubber or synthetic compounds; (2) fabric (cotton cloth or canvas); or (3) metal (either solid or in combination with rubber inserts).

Since the latter is used primarily for special applications, most of the following remarks will be devoted to the rubber- and fabric-type wheels.

Rubber-covered or synthetic compound (urethane) contact wheels are available in sizes ranging from under 1 inch in diameter to special designs in the 30- to 40-inch diameter range, each having its niche in application. Normal contact wheel diameters for off-hand work have usually been designed to generate sufficient clearance for workpieces in relation to bearing housings and, on fixed-speed machines, to supply a generally acceptable surface feet per minute (sfpm) speed for running the coated abrasive belt. Many widths, usually in ½- or 1-inch increments, are also available to accommodate convenient belt widths for the particular application.

The factors controlling the performance of rubber wheels are the following: (1) thickness of the covering; (2) hardness of the covering; and (3) wheel face design.

If serrated, additional factors are (1) angle of serration; (2) ratio of land to groove; (3) shape of land, width of land; and (4) depth of groove.

All of these factors determine the ability of a given abrasive belt to remove unwanted stock or produce a desirable finish.

Thickness of the Covering

The thickness of the rubber or synthetic covering, coupled with the density, will determine the amount of "cushion" or "give" on a particular contact wheel. A thin cover will not compress readily and may retard the capacity to develop finishes. Conversely, a cover that is too thick may give too much cushion and retard the wheel's cutting ability. General-purpose contact wheels are covered to a nominal radial thickness of ¾ inch, but special-purpose wheels may vary somewhat.

Hardness of the Covering

Unless otherwise stated, the hardness of rubber contact wheels is specified in Shore "A" scale durometer readings. The higher numbers denote harder compounds, and lower numbers represent softer compounds. Harder contact wheels will remove unwanted material at a faster rate than will softer contact wheels but produce a finish with a larger rms reading than a softer durometer contact wheel used with the same grit coated abrasive belt, and as would be expected, softer contact wheels will produce a superior finish at the expense of slower material removal. It is impossible for one contact wheel to give the highest rate of stock removal yet generate the best possible finish. Higher rotational speeds through centrifugal force cause contact wheels to perform harder and may have a detrimental impact on finishing.

Warning: Contact wheels should not be run at speeds in excess of manufacturers' recommendations and should always be used in conjunction with properly guarded equipment. Operators should wear OSHA-approved safety goggles and protective equipment such as leather aprons, safety shoes, and gloves.

Wheel Face Design

Selection of the correct geometry of the contact wheel face is probably the most important segment of contact wheel selection, at least equally rated with hardness selection.

The surface configuration and finish produced by a rubber contact wheel may be varied by the use of serrations. Serrations are actually grooves cut at an angle across the face of the wheel. Proper selection of the groove width and land width (the "land" is the remaining portion of the face that has not been cut away) can markedly increase stock removal rates, increase belt life, and even change the finish produced by a given grit-size belt. Wide grooves and narrower lands will make the cut more aggressive, and, as with hardness, the opposite is also true (i.e., an increase in the width of the land and reduction in the width of the groove will produce finer finishes), with a smooth or unserrated face producing the best finish.

For most off-hand finishing operations, it is impractical to change the contact wheel several times a day. This results in selection of a wheel that may not give the utmost in cut or belt life nor the best finish, but, when coupled with the proper coated abrasive belt selection, will produce satisfactory results. As conditions vary from shop to shop and job to job, it is nearly impossible to make one contact wheel recommendation that will give the utmost in results for all possible work combinations.

One of the final considerations in contact wheel selection is land and groove angle. Angle is always measured from the side of the contact wheel. The most aggressive angle and, hence, the poorest finish generator, would be 90°, or with the lands and grooves parallel with the bore; however, as air is trapped between the belt and contact wheel during rotation of the wheel, and forcefully expelled during the process, a severe, sharp whistling noise is generated, far above comfortable or safe levels. This high-decibel noise level, coupled with the severe hammering or chattering effect produced by the sharp, sudden contact of the lands with the workpiece, makes the selection of this angle of serration an unwise choice.

For off-hand polishing, the angle of serration seldom exceeds 45° and may be as low as 8°. Angles in the 60° range are not uncommon but are usually reserved for rolls incorporated in the higher horsepower finishing of a machine-held and controlled workpiece. *A word of caution:* The serration angle should never match the angle of a belt joint but should be cut so that the serration angle crosses the angle of a belt joint. Example: A 45° belt joint and a 45° serration angle would form a 90° angle when the belt is placed over the wheel face.

For most general-purpose work, when removal of excess stock is the prime consideration, contact wheels of 70 durometer, land-to-groove width of one part land to two parts groove, will normally give excellent results. If the wheel must produce commercial finishes as well as light stock removal, a land and groove ratio of 1:1 at a 45° angle built into a 60-durometer wheel will usually do an excellent job.

Cloth Contact Wheels

Contact wheels constructed of cloth are available in three designs: (1) solid buff type—made to desired width; (2) sectional, pleated buff sections; and (3) sectional finger buff.

The solid buff-types wheels are manufactured to a desired width and diameter and are not available with serrations and normally are not "ganged" together on a spindle to achieve a greater width for running wider belts. They are available in five densities, ranging from #50 on the soft side to #90 on the hard end of the scale. The hardness measurement on cloth wheels should not be confused with the durometer readings by which rubber or synthetic compound wheels are measured. For cloth wheels, the numbers are relative to allow more variations in manufacturing and use than merely the description soft, medium, or hard.

Solid buff-type wheels in the #50 range are the softest and most conformable to part radii, and, hence, the #90 are the hardest, most aggressive, and least conformable. All do an excellent job of developing fine finishes, run smoothly without excess vibration, and the softer densities allow moderate contouring. The same rule of thumb exists with solid buff wheels as with rubber wheels (i.e., the harder the wheel, the greater the aggressiveness; the softer the wheel, the finer the finish). Cloth wheels usually allow greater contouring ability than do rubber wheels, with the possible exception of sponge density (under 20 durometer).

Sectional, pleated buff sections offer the versatility of "ganging" two or more sections side by side to quickly build a wheel to the desired width. Care should be exercised to ensure that all sections in a wheel have been used or worn equally or a streaking condition of the workpiece may result. One or two sections of greater diameter will cause poor belt tracking, because the high sections will act as a crown, with the coated abrasive belt trying to center itself on the crown. This wheel offers somewhat more cutting ability than a solid buff-type wheel but usually at a lower wheel cost per inch of face width.

Sectional finger buffs offer the most flexibility of the cloth wheels and although somewhat lower in cutting ability, offer added contourability. Sectional finger buffs, too, have the advantage of lower cost and the capacity to quickly construct a wheel of needed face width.

All of the cloth-type wheels are excellent for developing fine finishes or prebuff finishes.

TRACKING AND TENSIONING DEVICES

Tracking and tensioning devices are more commonly called "backstand idlers" or "idlers" when used in conjunction with a contact wheel or drive pulley mounted on a powered shaft. The idler's purpose is to (1) keep the proper tension on the abrasive belt so the driving unit can transmit horsepower to the belt; and (2) provide the operator with a practical means of establishing the running path of a coated abrasive belt in relation to the contact wheel or platen over which the belt travels.

Idlers should be mounted on the floor where space and workpiece shape permit (Figs. 1 and 2).

In certain instances, where workpiece contours are such that the operator needs clearance below the contact wheel, the idler may be pedestal or wall mounted; however, it should be kept in mind that the more wraparound the coated abrasive belt has on the contact wheel before contacting the workpiece, the better the tracking control over the belt will be.

Wall-mounted idlers (Fig. 2) should be avoided wherever practical, provided that the belt is running in the normal, toward-the-floor, counterclockwise direction when viewed from the end of the drive shaft and contact wheel. With a belt running in this mode and utilizing a wall-mounted idler, only a small portion of the belt is in contact with the contact wheel before reaching the workpiece area and can easily be forced to track-off through work pressure alone, especially when soft contact wheels are used. If the belt is running in the opposite direction (i.e., clockwise or up and away from the operator when viewed from the shaft end position), this would have the reverse effect and provide the most stable belt tracking.

Idlers may be tensioned by air, hydraulically, by spring load, counterweighted, or through a simple operator-actuated screw adjustment (Fig. 3). The idler selection should be viewed carefully; too little or too much tension can have detrimental effects on the results received from the contact wheel. Belt tension can harden the face of soft contact wheels and, if excessive, can defeat the purpose of selecting a soft wheel. Reduced conformability, poorer finish, and tracking problems can be related directly to excessive belt tension. If there is a variety of workpieces to be finished, requiring contact wheel and belt changes, an idler incorporating fully adjustable tension is a must.

Tracking is accomplished by the majority of idlers by displacing the alignment of the idler shaft and contact wheel shaft, either vertically (Fig. 4) or horizontally, in a controlled manner. Tipping or pivoting of the idler shaft by the operator, through a mechanical linkage, causes the belt to track to the right or left and even partially off the edge of the contact wheel for work on radii.

Most idlers are crowned to varying degrees, depending on the type of pivoting mechanism used to track the belt. If a straight taper from each edge toward the center of the idler is used, the center diameter should be on the order of 1⁄32 inch larger than the pulley edges (Fig. 5). This gives enough variation in sfpm to keep the belt centered on the idler. Should this crown be worn off after much use, tracking troubles will result, and the crown should be regenerated.

It is not uncommon to have the taper wear so that the crown increases. Too much crown will also contribute to tracking problems and will cause the belt to depress the center of a soft contact wheel excessively, contributing to finish variation and folding of flexible belts.

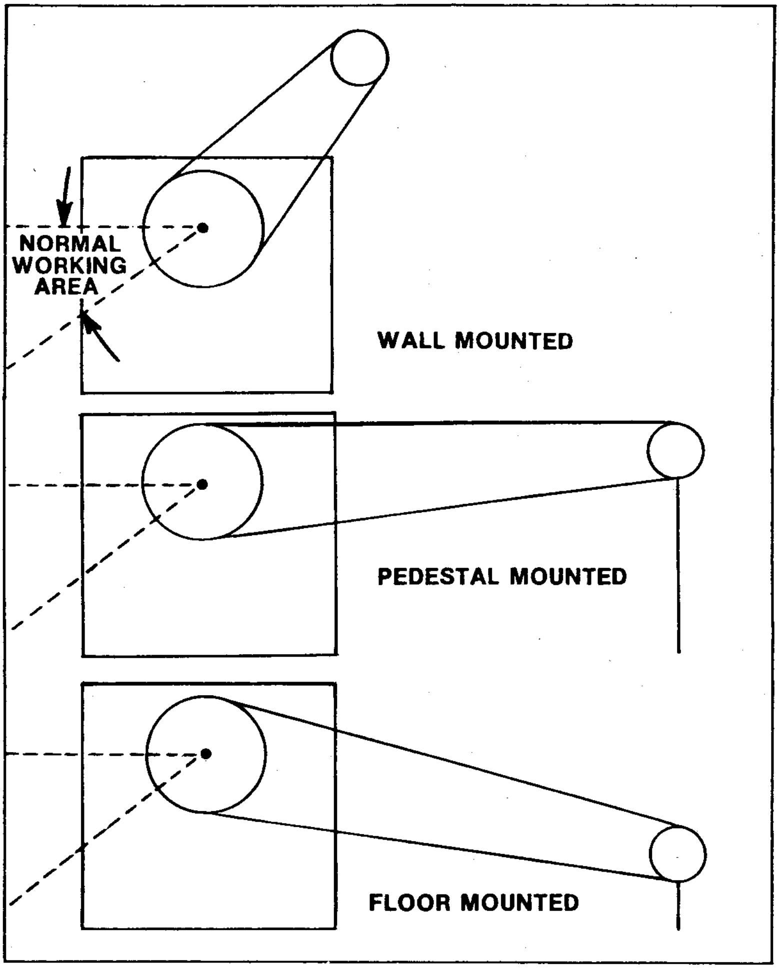


Fig. 2. Options for mounting idlers.

THE PROPER COATED ABRASIVE BELT

After proper selection of equipment, coated abrasive belt selection must be given stringent consideration. To better select the proper product combination, the components of a belt should be understood.

The term sandpaper is a misnomer, because the grit bears little actual resemblance to sand and the backing is much more complicated than the name "paper" implies. Various types of abrasive grain, adhesive, and backing materials make coated abrasive products very versatile tools for metal finishing. To achieve a better perspective for the complete product,

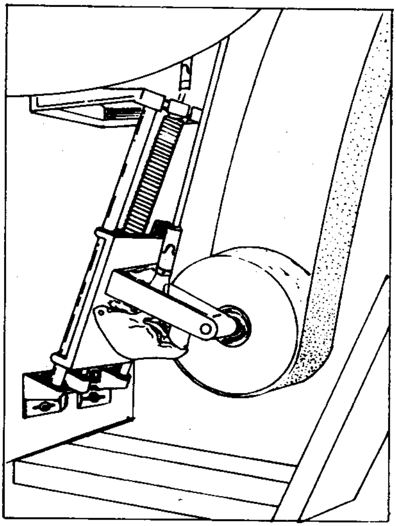


Fig. 3. Idler with operator-actuated screw adjustment.

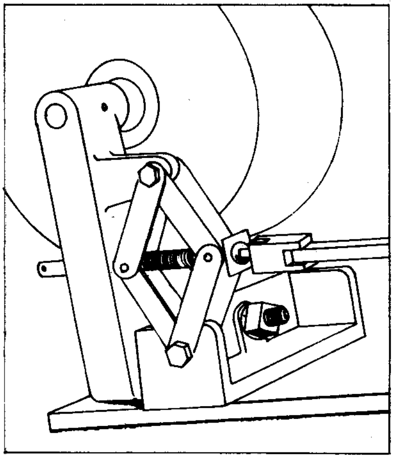


Fig. 4. Tracking is accomplished by displacing the shaft alignment.

each component must be understood. Backings may be manufactured of (1) paper; (2) cloth (either of natural fiber or man-made fiber); or (3) cloth and paper combined.

A cloth and paper combination is normally used as a backing for floor-sanding products. It is seldom used in the metal finishing trade. Paper backing, when associated with metal

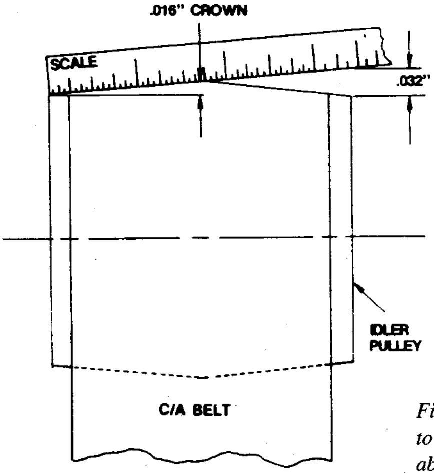


Fig. 5. An idler crown must be maintained to avoid tracking problems. C/A = coated abrasive.

finishing, is normally relegated to wide-belt use, which excludes handheld operations; however, a sizable quantity is used in the development of cosmetic finishes on stainless steel trim and flat surfaces where heavy grinding pressures are not normally used and there is little or no danger of snagging an edge on a hole or projection.

Fiber-backed products find their natural end use in heavy-coated abrasive disks or as covers for drum sanders. Since the advent of belt sanders, little metal is finished using the drum-sander type of equipment. The largest end use of fiber-backed coated abrasives is in disk form, and the popular sizes are 5, 7, and 9 inches. These are used with right-angle grinders in conjunction with a backing pad to support the disk during the grinding cycle. A typical use of a coated abrasive disk would be removal of excess weld bead.

Cloth-backed coated abrasives are the type with the largest end use in metal finishing. They combine the necessary strength, flexibility, and durability in a carrier for the abrasive grain. By varying the size, number, and type of threads in different woven constructions, many end-use requirements can be met.

A cloth of extreme flexibility will differ markedly from one used to provide a base for heavy grinding. So, to accommodate the wide needs of industry, the following different weights and constructions have been developed:

1. "J," or Jeans weight, is a very flexible, lighter weight cloth, used where conformation to contours and finish are prime requisites.
2. "X" weight, or drill cloth, is heavier than Jeans and for many years was the staple backing for what was then heavy stock removal.
3. "Y" weight is a newer, even stronger development for today's market, which is demanding stronger, more rugged abrasive products.
4. "S" weight is special-purpose cloth designed specifically for the manufacture of wide sectional belts.

Cotton has been historically the basic fiber used in producing these cloth backings; however, polyester fibers, which offer greater tensile strength and more resistance to fraying and tearing, are becoming the standard in coarse-grit sizes and are moving into the fine-grit areas.

Abrasive particles of natural materials, such as garnet, flint, and emery, at one time accounted for the largest portion of the grit used on coated abrasives but have been replaced for metalworking by the newer man-made abrasives of aluminum oxide, silicon carbide, zirconia alumina, and ceramic aluminum oxide.

Aluminum oxide, primarily Al_2O_3, is a tough, somewhat chunky-shaped grain ideally suited for most metalworking applications. It has the ability to withstand considerable grinding pressures before fracturing to expose new cutting edges.

Silicon carbide is a harder, more brittle abrasive than aluminum oxide; each grain has a longer axis and fractures more readily than Al_2O_3. In fact, on most metal applications, it fractures too readily, so that its use is relegated to very hard metals or very tough ones, such as titanium, or to the development of special stainless steel finishes.

Zirconia alumina, ZrO_2-Al_2O_3, is known for its exceptional durability under lighter grinding pressures and its ability to resharpen under heavy grinding pressure. Ceramic aluminum oxide is the newest manmade abrasive grain and is designed to break down and resharpen under lighter pressure than zirconia alumina in the 60-finer grit range and may be superior to zirconia alumina in the 50-coarser grit range, depending on the alloy.

The backing material and abrasive grain must be incorporated into the final product by a bonding process, using an adhesive such as glue, phenolic resin, urea resin, individually or in combination.

This bonding process is a two-step operation, consisting of a base coat, which may be glue or resin, and an additional layer of adhesive applied after the abrasive grain is deposited on the base coat. The second coat is commonly referred to as the size coat and may also be of glue or resin, depending on the intended market for the product.

THE ABRASIVE BOND

Glue bonds are used where the utmost in finish is the prime requisite of the operation. When they are combined with a "J"- weight cloth, excellent flexibility results. These products are used for fine finishes on parts with contours and are not designed for heavy stock removal. Glue bond products cut cooler than do resin bonded but are also less heat resistant. If an "X"-weight cloth is used as the carrier rather than "J" weight, a decrease in flexibility will be encountered, but finish should remain equal.

To increase the aggressiveness of a product and retain maximum flexibility, a coat of resin may be substituted for the size coat of glue. This will detract slightly from the finishing capability of the product but will increase its cutting capacity and life. The same comments on backing weight apply to this product type (i.e., "J" weight is more flexible than "X" weight). These resin-over-glue products are used where good flexibility is desired and finish is not of prime concern.

When an all-resin bond is coupled with an "X"- or "Y"-weight cloth, the maximum in durability, aggressiveness, and productivity of the coated-abrasive grain is achieved. Because of the heavier backing and stronger, tougher bond, it would be reasonable to expect a marked decrease in flexibility. Generally this is true, but on certain specialized products, techniques have been developed to retain an excellent degree of flexibility. When selecting an all-resin product, if the operation to be performed requires moderate flexibility in the belt, a representative from the manufacturer of the coating should be consulted.

EFFECT OF SURFACE SPEED

Assuming that the correct components have been selected and properly installed (i.e., correct power, contact wheel, idler, and coated-abrasive belt), two added factors that now must be considered (Table II) are surface speed of the belt and grinding aids.

If each individual abrasive particle on a belt is thought of as a single-point cutting tool, perhaps a better perspective of the abrasive action can be established. The speed of the belt or number of times a minute each particle contacts the work in a given time frame, will determine the rate of removal and the working life of the individual particle, assuming that the conditions of pressure and workpiece consistency remain constant. An increase in the surface speed will cause the pressure to be applied to many more particles in a given time frame and will reduce the penetration of a given particle into the workpiece. When this speed reaches beyond a critical point, rapid dulling of the abrasive grain takes place, the rate of cut decreases, and excess heat is generated.

To resharpen or restore the cutting capacity of the abrasive, added pressure must be exerted to cause fracture of the grain. This added pressure will generate added heat and, shortly, part burning or operator sensitivity will result in the removal of the belt. Conversely, as speeds are slowed, more pressure is exerted on each grain, causing the grain to resharpen with less heat generation. To put this in better perspective, refer to Table II, where suggested speeds, abrasive, contact wheel, grit size, lubricant, and operation have been coordinated into a quick, accurate reference chart.

BELT LUBRICANTS

Lubricants may serve several purposes when the proper one is used. They may be used to retard metal welding to the grain (as in the grinding of aluminum), improve the finish, extend the belt life, increase the aggressiveness, or a combination of any or all of these benefits.

Table II. Suggested Surface Speed and Abrasives for Various Metals

Material	*Operation*	*Abrasive*[a]	*Grits*	*Belt Speed*	*Lubricant*	*Contact Wheel Type*	*Hardness/Durometer*
Hot and cold rolled steel	Grinding	ZA, A/O, or CAO	24–60	4,000–7,000	Dry	Cog tooth or serrated	70–95 duro.
	Polishing	ZA, A/O, or CAO	80–150	4,000–7,000	Dry or light grease	Plain face rubber, canvas	40–70 duro. medium
	Fine polishing	A/O	180–320	4,000–7,000	Heavy grease or polishing oil	Plain face rubber, canvas, cloth	Soft
Stainless Steel	Grinding	ZA or A/O	36–60	3,000–5,000	Dry	Cog tooth or serrated	70–95 duro.
	Polishing	ZA or A/O	80–150	3,000–5,000	Dry or light grease	Plain face rubber	40–70 duro.
	Fine polishing	A/O or S/C	180–240	3,000–5,000	Heavy grease or polishing oil	Plain face rubber, canvas, cloth	Soft
Aluminum	Grinding	ZA, A/O, or CAO	24–80	4,000–7,000	Light grease	Cog tooth or serrated	70–95 duro.
	Polishing	A/O or S/C	100–180	4,000–7,000	Light grease	Plain face rubber	40–70 duro. medium
	Fine polishing	A/O or S/C	220–320	4,000–7,000	Light grease or heavy grease	Plain face rubber, canvas, cloth	Soft
Copper and copper alloys	Grinding	A/O or S/C	36–80	3,000–7,000	Light grease	Cog tooth or serrated	70–95 duro.
	Polishing	A/O or S/C	100–150	3,000–7,000	Light grease	Plain face rubber, canvas, cloth	40–70 duro. medium
	Fine polishing	A/O or S/C	180–320	3,000–7,000	Light grease or heavy grease	Plain face rubber, canvas, cloth	Soft
Nonferrous die castings	Grinding	ZA, A/O, or CAO	24–80	5,000–7,000	Light grease	Serrated or plain	70–95 duro.
	Polishing	A/O or S/C	100–180	5,000–7,000	Light grease	Plain face rubber, canvas, cloth	40–70 duro. medium
	Fine polishing	A/O or S/C	220–320	5,000–7,000	Light grease or heavy grease	Plain face rubber, canvas, cloth	Soft
Cast iron	Grinding	ZA, A/O, or CAO	24–60	2,000–5,000	Dry	Cog tooth or serrated	70–95 duro.
	Polishing	ZA or A/O	80–150	2,000–5,000	Dry	Serrated or plain	40–70 duro.
	Fine polishing	ZA or A/O	150–240	2,000–5,000	Light grease	Plain rubber	30–50 duro.
Titanium	Grinding	ZA or S/C	36–60	1,000–2,500	Dry	Cog tooth or serrated	70–95 duro.
	Polishing	S/C	80–120	1,000–2,500	Light grease	Serrated or plain	40–70 duro.
	Fine polishing	S/C	150–240	1,000–2,500	Light grease	Plain face rubber, canvas, cloth	Soft

[a] ZA = zirconia alumina; A/O = aluminum oxide; CAO = ceramic aluminum oxide; S/C = silicon carbide; duro. = durometer.

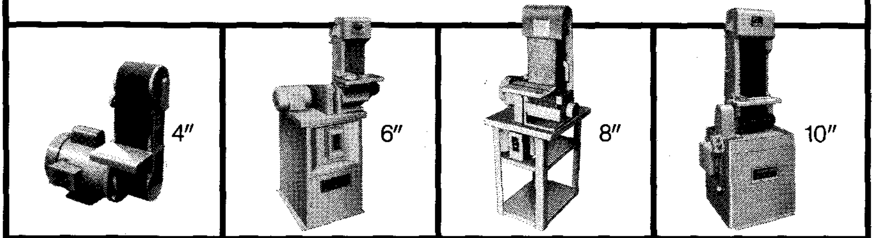
Light-bodied grease sticks are normally used to prevent loading or metal welding on the abrasive grain. Lubricant should be applied before work is presented to the belt and at frequent intervals during its life cycle. This is especially important when working with nonferrous materials. Most light-bodied grease sticks do not retard the rate of cut received from a belt, and after long service, the spaces between the abrasive grains may become clogged with ground-off material entrapped in the lubricant. Degreasing the belt will remove this type of loading, and added service may be received from the abrasive.

Heavy-bodied grease sticks perform a dual role. They will slightly retard grain penetration into the workpiece, producing a finish actually finer than would be generated by a dry belt; they will retard loading and will act as a "heat sink," causing the part to grind somewhat cooler. Grease sticks containing sulfur and chloride will aid cut and life on chromium-nickel alloys but should not be used on materials that will react negatively and discolor metals such as brass, aluminum, and copper.

The finish produced by a dry belt may require twice the time to buff out, compared to the same grit belt that has been lubricated. As an example, a dry belt may, under a given set of conditions, produce a finish in the 30- to 35-rms range, but by greasing the same belt, finishes in the range of 10 to 12 rms are not uncommon.

If the part is to be buffed, a careful cost study should be done on the preparation and ensuing time to buff. For example, a worn belt may produce the same rms as a finer grit but newer belt; however, the surface produced by the coarser grit belt will have wider scratch lines than the finer grit and may need up to twice the buffing time to remove.

The finish received from a belt will vary from the first part produced to the last part produced. Usually, the rms on a given belt will improve rapidly during the first 10 to 25% of its life, depending on pressure, workpiece material, etc., then slowly drop over the next 75 to 90% of its life. In this area, most of the productive life of the belt is obtained and the most uniform finish is produced. Frequently, an operator will "break in" a new belt or set aside the first parts produced to be rerun after the stable portion of rms has been reached.



FILAMENTARY BRUSHING TOOLS FOR SURFACE FINISHING APPLICATIONS

by Robert J. Stango

Deburring and Surface Finishing Research Laboratory, Department of Mechanical and Industrial Engineering, Marquette University, Milwaukee

Filamentary brushes have been used for many years in both manual and semiautomated surface finishing operations. More recently, brushes have been used in numerous fully automated applications, including surface preparation, burr removal, and polishing operations. The widespread use of brushes for such applications may be attributed to the inherent efficiency and the relative ease with which the tool can be implemented in either manual or automated surface finishing processes, i.e., the compliant fibers readily conform to contours of the workpart surface and exert small, evenly distributed machining forces that gradually remove material. This, in turn, permits controlled material removal, simple workpart fixturing, and reduces the risk of accidentally overmachining or damaging the workpart.

Brushes are fabricated from a wide range of natural fibers, metallic wires, and abrasive-filled polymeric materials, and are available in an array of geometric shapes and sizes. The geometry of a circular brush, for example, is illustrated in Fig. 1a for two different types of fibers, namely nonstraight (crimped) metallic fibers with a single cutting edge (Fig. 1b) and polymer/abrasive fibers with multiple cutting edges (Fig. 1c). The geometric specification of this brush is given by overall diameter D, width W, hub radius r_h, filament trim length L, fiber diameter d, and the total number of filaments N, which occupy the working surface of the brush. For reference purposes, several types of brushing tools are shown in Fig. 2a–f, including a circular brush with crimped wire (Fig. 2a), circular brush with twisted-knot wire (Fig. 2b), cup brush with crimped wire (Fig. 2c), end brush (Fig. 2d), abrasive ball honing brush (Fig. 2e), and adjustable nylon/abrasive honing brush (Fig. 2f).

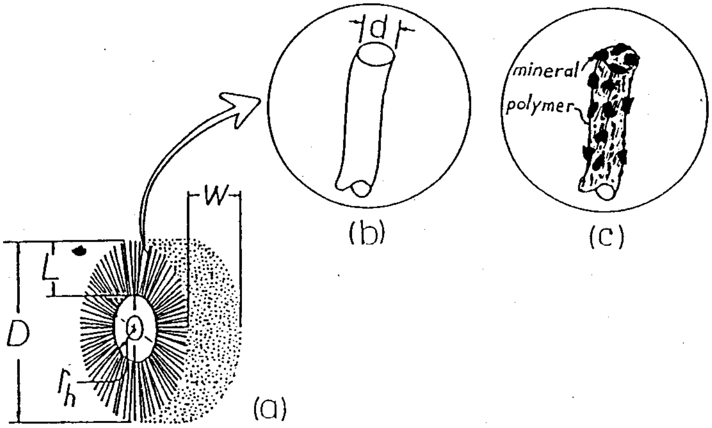


Fig. 1. (a) Geometry of conventional circular filamentary brush, (b) wire filament geometry, and (c) nylon/abrasive filament geometry.

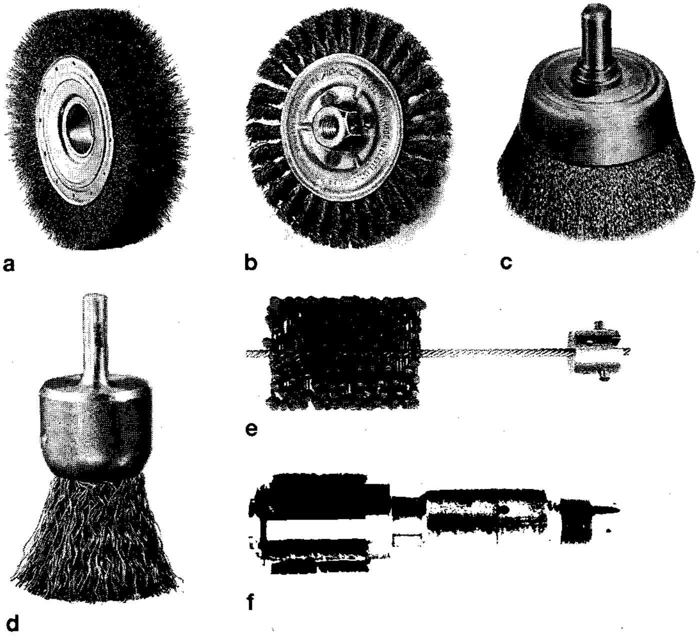


Fig. 2. Common brushing tools including (a) circular brush, (b) circular brush with twisted-knot wire, (c) cup brush, (d) end brush, (e) abrasive ball honing brush, and (f) adjustable nylon/abrasive honing brush.

TECHNICAL ISSUES

The material removal and surface finishing performance of brushing tools are principally derived from forces exerted by fibers of a specific geometry and material composition onto a workpart surface. This filament/workpart interaction results in "score markings" along the workpart surface, which are associated with the formation of microchips and/or plowing during the machining process. One may observe that, for brushes composed of metallic fibers, the filament diameter and filament population are closely related to the surface texture generated by the brushing tool. For example, it is presumed that the score markings generated by brushes comprised of large wire diameter yield a coarse surface texture, whereas those fabricated from thin wire yield fine surface texture. In addition, for brushes having the same width and fiber diameter, greater filament population can result in a more uniform surface texture than those generated by brushes having sparse filament population. Although this qualitative information may prove helpful in assessing the surface texture that is produced by brushing tools, further information concerning brush stiffness is needed in order to characterize the operational forces that must be applied during the material removal process.

BRUSH/WORKPART CONTACT

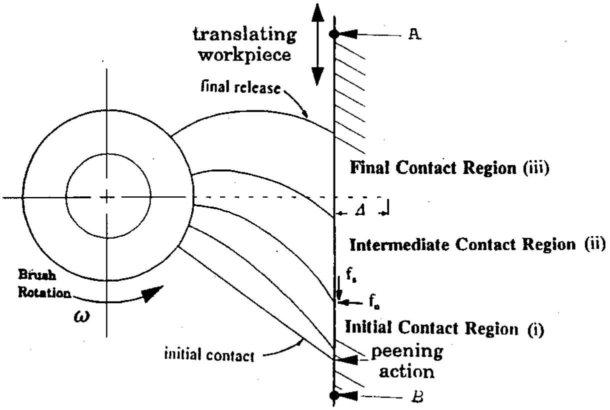


Fig. 3. Geometry and force system of circular brush in contact with flat workpart surface.

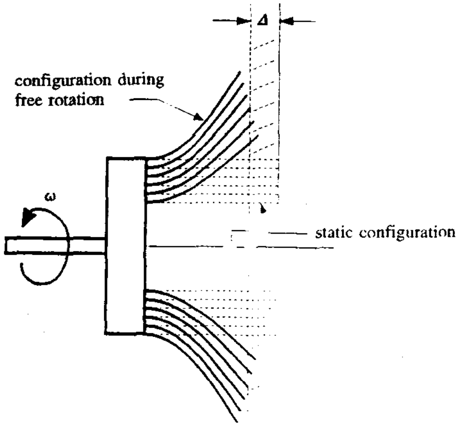
In Fig. 3, a circular filamentary brush is shown in orthogonal contact with a flat workpart surface and is subjected to penetration depth δ during brush rotation. Throughout the brushed region, normal and shear filament contact forces f_n and f_s, respectively, are generated as each fiber undergoes intermittent contact with the workpart surface. These forces are associated with the actual material removal processes and, thus, have been the subject of considerable investigation in recent years.[1–3] An overall friction coefficient $\mu = (\sigma f_s/\sigma f_n)$ has been measured for several dry-brushing processes and typically ranges from <0.25 μm (polishing) to <1.0 μm (heavy material removal).

The position of filament tips within the contact zone (reference, Fig. 3) are shown at (i) the initial region of contact, (ii) some intermediate position, and (iii) near the end of the contact zone. Some important observations regarding the nature of filament/workpart contact within these three regions of the contact zone are summarized below:

Initial Contact Region. The magnitude of the filament force exerted onto the workpart surface within the initial contact region can vary significantly with brush rotational speed.[4,5] For example, at relatively low brush speeds, the force exerted by the filament tip is initially small and progressively increases as the fiber tip continues toward an interior location within the contact zone. Under such operating conditions, the material removed from the workpart (i.e., machining depth) increases gradually according to the local filament force. At higher brush speeds, however, significant impact forces can develop at the filament/workpart interface as the fiber enters the contact zone. This can give rise to locally enhanced machining performance and altered surface texture. In addition, it is currently held that filament impact forces can result in local peening of the workpart surface along with the usual accompanying benefits, namely, increased workpart hardness and a compressive residual stress state. Such surface modification can lead to an improvement in both wear resistance and fatigue life.

Intermediate Contact Region. The intermediate region of the contact zone is typically characterized by stable machining forces at the interface of the fiber/workpart surface. At conventional brush speeds, this portion of the contact zone is subjected to greatest filament force and, thus, a maximal rate of material removal is obtained.

Fig. 4. *Cross-sectional view of cup brush in both static (dotted lines) and steady-state rotation (solid lines) configuration.*



Final Contact Region. Throughout the final region of contact, both the filament force and material removed from the workpart surface is gradually reduced as the fiber tip approaches the final point of contact, whereupon the fiber abruptly departs from the workpart surface.

Based upon the above discussion, it is apparent that both the brush rotational speed and the workpart feed direction play an important role in the final texture, appearance, and mechanical properties of the brushed region. Examination of Fig. 3, for example, indicates that downward movement of the workpart results in final contact of point A within region (i). In this case, properties of the brushed workpart would be characteristic of a peened surface. A reversal of the workpart feed direction (i.e., upward), however, results in gradual machining of the peened surface, as point B progresses through the intermediate and final region of the contact zone.

The contact mechanics for orthogonal use of cup brushes is fundamentally different from circular brushes. During full-faced contact of a cup brush with a flat surface, filaments remain in steady contact with the workpart along the annular brushed region, and previous comments regarding filament impact forces are no longer applicable; however, centrifugal filament forces that are generated during cup brush rotation can result in nonuniform filament/workpart contact and, therefore, preferential material removal within the contact zone is inevitable. This phenomena is illustrated in Fig. 4, whereby the cross-sectional view of a rotating cup brush shows that the engagement of fibers within the contact zone is greatest along the inside perimeter, and least along the outside perimeter of the brush. Cup brushes are sometimes used in nonorthogonal (i.e., oblique angle) contact brushing applications. In such cases, filaments undergo intermittent contact with the workpart surface and, therefore, one may anticipate material removal performance similar to circular brushing tools.

FILAMENT MATERIALS

Brushes are fabricated from a wide range of filamentary materials including metallic, nylon abrasive, and natural fibers. Each of these fibers exhibit unique performance when used in surface finishing applications and, thus, are discussed separately below.

Metallic Fibers

Metallic fibers, whether steel, brass, or bronze, each form a *single* cutting edge at the interface of the filament/workpart. Thus, the geometry and depth of the score markings that are generated along the machined surface are closely related to both the wire diameter and force exerted by the filament onto the workpart surface. Generally, the most rapid material removal and coarsest texture are obtained when larger wire diameter is used in conjunction with a shorter trim length, whereas less material is removed and finer surface texture is obtained by employing smaller wire diameter and/or increasing the trim length. Due to the important role that fiber diameter and fiber length play in machining performance, brushes are offered in a wide range of wire sizes in order to satisfy the machining performance that is required for a specific brushing application. Filamentary brushes are most commonly fabricated from steel wire, as this material has greater strength, hardness, and resistance to wear/damage than nonferrous materials. Nonferrous wire brushes are also available and can be used in applications where special machining characteristics are necessary, as discussed in a later section, below.

Nylon/Abrasive

This class of brush fibers consists of two discrete materials, namely, a working mineral such as silicon carbide or aluminum oxide, and nylon. The working mineral is uniformly dispersed (~40% by weight) throughout the nylon and leads to *multiple* cutting edges at the interface of the fiber tip/workpart surface. In this case, the dimension of the score markings generated along the workpart surface is determined by the size of the mineral as well as the force exerted by the fiber.

Nylon/abrasive fibers are available in grit sizes ranging from 46 (largest) to 500 (smallest), where larger grit sizes generate coarser texture, and smaller grit sizes generate finer texture. The relatively low melting temperature of nylon can pose a significant restriction on brush operating conditions. For example, excessive brush speed can cause melting/deposition of nylon onto the workpart surface. Although detailed guidelines for brush use are not yet available, this problem can often be circumvented by selecting brush surface speeds less than 2,600 ft/min.

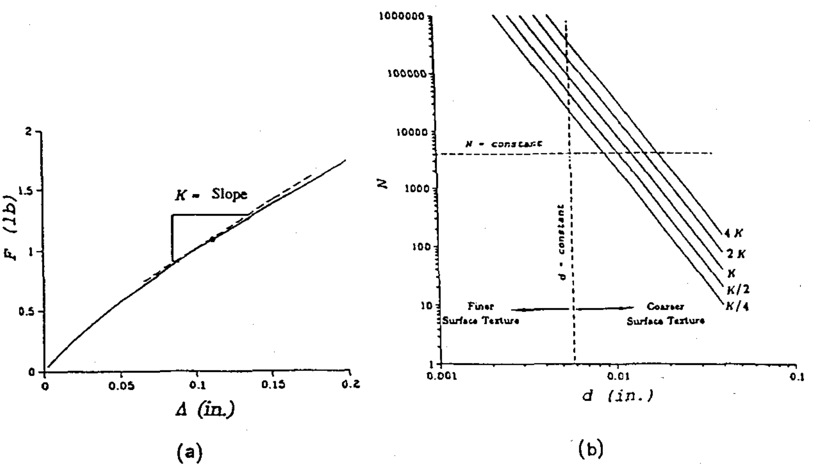
Unfilled Polymeric and Natural Fibers

This variety of fibers is frequently used in brushing applications for surface cleaning and/or enhancing surface appearance. Unfilled polymeric fibers, such as nylon and polypropylene, and natural fibers, including tampico and palmyra, do not generate score markings and, thus, have little or no effect on surface texture. The force exerted by fiber tips can, however, remove loosely attached particles/debris, and can result in some alteration of surface appearance. As noted earlier, polymeric materials have a relatively low melting temperature and, therefore, operating conditions must also be chosen for this variety of fibers to circumvent melt/deposition.

BRUSH STIFFNESS AND MACHINING PERFORMANCE

As shown in Fig. 5a, the stiffness of a brushing tool is defined by the local slope S of the total force versus penetration depth brush response. Brush stiffness is an important parameter for both manual and automated brushing operations because it describes the actual range of forces that must be applied by the person or machine system during the material removal operation. In addition, the relative stiffness of two different brushes can provide helpful information concerning their relative material removal rate performance, as described below.

Recently completed research[6] has shown that brush stiffness can be readily computed in terms of filament diameter d, and the total brush filament population, N. This, in turn, can facilitate the design and manufacture of brushing tools with predictable stiffness and machining performance. As shown in Fig. 5b, for example, a "family" of filamentary brushes can be fabricated, which possess *constant* stiffness or *proportional* stiffness, by strategically



(a) (b)

Fig. 5. (a) Definition of brush stiffness response K for filamentary brush having the following specifications: r_h = 1.5 in., L = 1.5 in., d = 0.008 in., N = 24,600, and E = 30 × 10^6 psi (i.e., steel wire), and (b) relationship between filament population N and fiber diameter do for brush systems having constant and proportional stiffness. (Note: Primary stiffness response [line bearing label K in Fig. 4b] is based upon any filamentary brush having the following dimensions: $r_h/L = 1.0$, and $d^4N = 10.08 \times 10^{-5}$ in^4.

altering the filament diameter *d* and filament population *N*. Moreover, these brushes have an identical overall diameter and filament trim length. Several observations can be made regarding the potential benefits that can be derived by using such brushes.

Brush selection and brush use are simplified because one may anticipate the inherent stiffness, surface finish characteristics, and material removal rate capability of a brush without trial and error experimentation. For example, if brush stiffness is increased and wire diameter is fixed (i.e., vertical line in Fig. 5b), then one may expect a corresponding increase in material removal rate with little change in surface finish texture. Conversely, one may achieve an improved surface finish texture by using a series of brushes that have identical or proportional stiffness in conjunction with a progressively smaller wire diameter (i.e., horizontal line in Fig. 5b).

Automated brushing operations that utilize a preprogrammed path for edge or surface finishing applications need not be reprogrammed for this class of brushing tools because the diametral dimensions of all brushes are identical.

The availability of a series of brushes that have equivalent stiffness can simplify the implementation of advanced automated brushing processes because the dynamic response of the brush/machine system will be unaffected by brush changeover.

APPLICATIONS

In this section, several commonly encountered brushing applications are identified and discussed. An attempt has been made to identify the general types of brushes that are most suitable for carrying out certain applications. Previously discussed issues concerning the basic machining performance of brushes should prove helpful in choosing a brush or series of brushing tools that lead to expedient material removal and/or desired surface texture. Specific recommendations for brush selection, however, can only be made when the constraints/requirements that are peculiar to the finishing application have been completely determined.

Texturing

Many brushing applications are concerned with altering or enhancing the surface texture that was generated by previous machining, forming, or finishing operations. Three commonly encountered brush texturing applications can be identified.

Texture Specification

Functional surfaces are often specified in terms of the required arithmetic average roughness height parameter, R_a. It is currently presumed that brushing tools can generate surface textures that range from 512 microin. for brushes comprised of larger wire diameter, to 16 microin. for brushes that employ fine grit nylon/abrasive fibers; however, the exact correlation between texture parameter R_a and the corresponding fiber chosen for the brushing operation is not yet known and, therefore, experimentation is often required.

Surface Preparation

The term surface preparation suggests that an existing surface must be altered from its present form to accommodate subsequent processing, such as painting, plating, or adhesive joining operations. Such applications may not be accompanied by strict requirements for surface texture parameter R_a. For example, general coarsening of a smooth surface may be necessary, as this increases the area of surface exposure and typically yields an improvement in the interfacial adhesion of subsequently applied coating/adhesive materials. Preparation of hard surfaces such as steel may require the use of nylon/abrasive brushing tools, whereas surfaces of lesser hardness can utilize wire or nylon/abrasive brushes.

Aesthetics/Appearance

This category of applications is principally concerned with generating a finished surface that possesses consumer-appealing attributes. Such brushing operations often involve generating or enhancing fine surface features (i.e., <64 microin.) and can require the use of additional surface finish descriptors, such as luminance, luster, and gloss, for specifying desired surface qualities. Brushes that are used for generating such finishes are typically fabricated from either fine diameter wire, nylon/abrasive, unfilled polymer, or natural fibers. As previously noted, brushes comprised of unfilled polymeric or natural fibers may have a benign effect on the alteration of roughness parameter R_a.

Edge Finishing

Various machining and materials processing operations, such as cutting, forming, and casting, can sometimes produce unacceptable edges along workpart boundaries. This may require the use of specialized tools that are used for edge finishing operations. Two important applications that involve the use of brushing tools for edge finishing operations are identified below.

Deburring

The machining of ductile materials often produces burrs along the edge where the machine tool enters or exits the workpart surface. Although most machining burrs are less than 1⁄32 in., larger burrs can be generated during heavy material removal applications.

Larger burrs that are formed along the edge of materials having considerable hardness, such as steel, may require the use of brushes comprised of steel wire, whereas smaller burrs can be readily machined using nylon/abrasive brushes. In either case, burrs can be efficiently removed by using the brush as depicted in Fig. 6. After the burr has been removed, continued

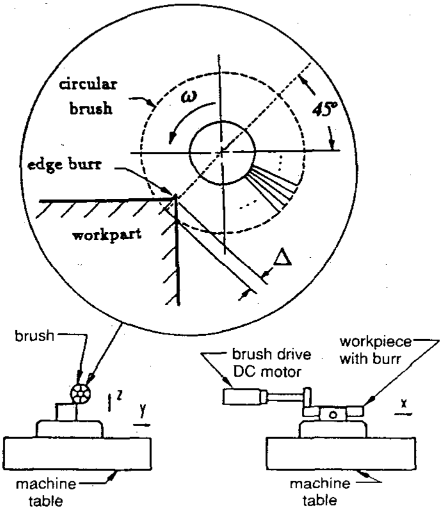


Fig. 6. Brush/workpart set-up used in edge deburring operations.

brushing of the workpart edge can lead to a nearly precise edge radius.[6] Thus, simultaneous burr removal and edge radiusing can be accomplished in a single brushing operation.

Deflashing

Metal casting and plastics molding operations often produce extraneous material known as "flash" along the edge of the molded part wherever dimensional disparity exists between the mold's mating components. Flash differs from previously discussed machining burrs in both size and shape. Larger components can result in flash having a height that is nearly ten times greater than burrs. In cases where the flash has significant thickness, brushing tools may not be suitable for their complete removal; however, thin sections of flash are most often generated during casting and molding operations and, thus, brushes are well suited for flash removal applications. Although recommendations for brush selection and brush/workpart set-up for deflashing operations are similar to those cited for deburring operations, special consideration may be required in choosing both brush speed and penetration depth. As in the case of deburring operations, further brushing of the workpart edge can produce a nearly precise edge radius.

Blending

Surface blending refers to machining operations that are aimed at "smoothing" surface anomalies. Such anomalies can be local, as in the case of parting line defects, cutter mismatch, and various forms of surface damage (i.e., scratches, gouges, etc.), or general, as in the case of cast or machined surfaces having an irregular or coarse surface. In either case, brushes can be used for reducing or eliminating surface anomalies. Blending of superficial defects can often be accomplished by a single brushing operation involving the use of wire or nylon/abrasive brushes, whereas defects having greater surface disparity may require the use of aggressive wire brushes and, if necessary, further surface treatment with brushes that subsequently generate finer texture.

Blending of local surface anomalies often results in surface waviness due to the inherent nonselective material removal characteristics within the brush/workpart contact zone. Nevertheless, nominal waviness is generally an acceptable surface configuration that accompanies blending operations. The precise location of the brush on the workpart surface that leads to the most efficient and expedient blending of local surface anomalies is difficult to assess. As previously noted, material removal can be significantly biased toward the initial region of brush/workpart contact at higher brush speeds. This phenomenon is not clearly understood and, thus, accurate guidelines are not yet available for predicting the proper use of brushes at elevated speeds during blending operations.

Stripping

Stripping operations involve the use of brushing tools for gross removal of a previously deposited film or adherent such as paint, coating, or plating material. In such applications, it may be desirable, or required, that the workpart (substrate) material remain virtually undisturbed. Thus, the composition of the coating material, as well as the hardness and durability of the workpart surface, can play a key role in selecting the proper brush for film removal. For example, a polymeric coating can be efficiently removed from a steel workpart surface without appreciable damage to the substrate by employing a small diameter steel wire brush, whereas the same coating could be removed from a brass workpart without generating substrate damage by employing a brass wire brush.

GENERAL CLEANING

Cleaning, or decontamination, implies that undesirable layers such as oil residue, corrosion, or scale must be removed from the surface. In this case, the thickness of the foreign layer is generally much smaller than those encountered on stripping operations, and the final surface must be free from contaminating substances. It may also be necessary that the substrate remain virtually undisturbed after the cleaning operation is performed.

The following guidelines can facilitate the selection and use of an appropriate brushing tool: (1) Machining forces exerted by the brush must be sufficient for removal of the foreign material and, if necessary, minimize material removal from the workpart surface. (2) The working surface of the brush should remain clean so as to not reintroduce the contaminating substance onto the workpart surface. (3) Fibers that comprise the brush, as well as brush operating conditions, must be chosen that do not introduce undesirable compounds onto the workpart surface. For example, stainless steel wire brushes are often used in applications involving food-processing equipment to minimize contamination by iron-containing compounds. Also, the selection of excessive speed for nylon/abrasive brushes must be avoided, as this can lead to deposition of nylon onto the workpart surface.

WELD CLEANING

Metal welding processes can produce a residual layer of slag along the welded joint that has potentially corrosive properties. Also, metal particles that are expelled during certain welding operations (i.e., "spatter") can become attached to the welded structure at random locations near the weld. Brushes comprised of steel wire are used for removing both slag and spatter. Post-weld cleaning operations that require removal of slag and spatter often utilize twisted-knot steel wire brushes (Fig. 2b). This variety of brushes possesses very high stiffness for expedient material removal. The machining performance is further enhanced by selecting brushes having tightly wound full cable construction with greater length, as this configuration leads to significant impact force at the initial point of entry in the contact zone.

HONING

Brush honing tools consist of a spherical abrasive compound attached to straight, flexible fibers that emanate radially from a central spindle (Fig. 2e). These tools are commonly used for removing the torn and folded metal that is generated during conventional honing operations that employ abrasive expansion sticks. During the cylindrical brushing process, the honing tool is simultaneously subjected to axial oscillation, which ultimately produces a desirable helical pattern or "cross-hatched" surface texture along the cylinder wall of internal combustion engines. These tools are often operated at relatively low spindle speeds (<900 rpm) and low penetration depth (<0.1). It has been reported[7] that a more uniform material removal performance may be obtained over the life of the tool by employing an increased brush penetration depth and/or altering the speed of the tool during latter stages of brush life.

Recently, brush honing tools have been made available that utilize nylon/abrasive fibers in conjunction with adjustability for diametral expansion (Fig. 2f). Such tools may also be used for the refinement of undesired surface texture, which is generated during conventional brush honing applications.

Acknowledgements

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BLAST FINISHING

by Daniel Herbert

Empire Abrasive Equipment Co., Langhorne, Pa.

Blast finishing, with all its variations, is powerful enough to remove heavy mill scale and rust or gentle enough to take paint off delicate aircraft skins. Blasting is used for finishing, cleaning, coating removal, surface preparation, and surface treatment. Here are some common applications of this versatile process:

Finishing: Add matte or satin finish, frost, decorate, remove glare, blend tooling marks and imperfections, hone and burnish, and mark identifications.

Cleaning and removal: Rust/oxidation, coatings, paint, sealants/adhesives, carbon deposits, excess brazing, casting medium, flash, and burrs.

Surface preparation: Etch for bonding and adhesion of subsequent coatings, expose flaws for inspection, and remove hard cast surfaces for subsequent machining.

Surface treatment: Shot peen for increased fatigue resistance, strengthen, increase wear properties, improve lubrication, reduce design weights, reduce susceptibility to corrosion, seal porous surfaces, and correct distortion.

Several blasting methods and a variety of equipment options are available to do the job. Blast cabinets are self-contained units where the user is isolated from the process for safety. Cabinet enclosures are used for manual systems where an operator accesses the part through rubber gloves. Larger blast rooms require the operator to suit up to blast very large parts. Automated machinery uses an enclosure to protect passersby. Dust removal and grit reclamation are usually integral to all blast systems.

Media selection plays an important role in effective blasting. Many kinds of manufactured and natural abrasives, ranging from 12-gauge mesh to powders, can be used. Depending upon the amount of pressure exerted through the blast nozzle and the surface being processed, each type of media can achieve different results.

The finishes produced by blasting are almost limitless. Change a few variables and the results can change dramatically. It is important, therefore, to "lock-in" the variables after the right combination has been found for consistent, high-quality results.

BLAST METHODS

There are many ways to deliver the working medium to the surface being treated, including compressed air, mechanical, and water slurry. The most popular is compressed air.

Air Blast

Air blast is categorized into two methods of media delivery: suction blast and pressure blast.

Suction blast systems are selected for light to medium amounts of production and moderate budgets. Suction is not as efficient as pressure, so the range of applications is more limited, but it often yields comparable results. Suction systems have the ability to blast continuously without stopping for media refills. They are also simpler to use and have fewer wear parts, making them inexpensive and easy to maintain.

Suction systems work on the principle that air passing over an orifice will create a vacuum at that point. This action takes place in the hand-held suction gun, with a media hose connected from the vacuum area to a media storage hopper. Compressed air is piped into the back of the gun and causes the lifted media to be blown out of a nozzle on the front of the gun. Energy is expended indirectly to lift the media and then mix it with the compressed air, making suction less efficient than a pressure system.

Pressure blasting feeds media into the compressed air stream at a pressurized storage vessel. The media then accelerates in the air stream as it is routed by a blast hose to the nozzle. Resulting media velocity is often several times that of a suction system, resulting in a common fourfold increase in production.

Direct pressure uses force, rather than suction, so it offers much more control at very high and very low operating pressure. Low pressure is used for delicate or fragile substrates, such as removing carbon from aluminum pistons or flash from integrated circuits. High pressure may be necessary for removing a tight mill scale. Direct pressure systems are especially useful for finishing hard-to-reach recessed areas and odd shapes, and in the case of very demanding applications (such as removing tight mill scale), they may be the only choice.

Options for Air Blast Systems

A variety of options is available for suction and pressure blasting systems. Options can tailor the system to your needs for increased productivity, material handling, longevity, and ease of use. Many of these will come as standard equipment with the cabinet, and most can be added after the fact without difficulty .

Media reclaimers remove useless dust and debris from otherwise reusable media and are generally included in production blasting systems. The reclaimer aids economy by reducing media waste, keeping blasting speed constant, and improving finish consistency by reentering media particles in the proper size range only.

Spent media, dust, and debris are conveyed pneumatically from the bottom of the blast cabinet to the reclaimer inlet. Heavier particles are thrown against the reclaimer wall, where there is less air movement due to laminar flow, and are pulled down to the storage hopper by gravity. Debris is screened off there. Lighter particles and dust enter a counter vortex in the center of the reclaimer and are sucked off to a dust collector.

Dust collectors filter dust-laden air from the blast cabinet or reclaimer, if so equipped. A dust collector will allow plant air to be recycled back into the plant, saving heat or air conditioning costs. Many states now mandate and regulate dust collector use.

There are two general types of dust collectors used for dry blasting: bag and cartridge. Traditional bag collectors trap dust on a cloth filter, usually cotton. Cleaning these bags is accomplished with a rapping mechanism that can be automated. Cartridge collectors are generally more efficient and are typically self-cleaning but are more expensive.

Extended wear packages protect vulnerable surfaces inside the system from wear. A typical package includes rubber curtains for the cabinet walls, heavy duty conveying hose, reclaimer wear plates, and carbide nozzles.

Air dryers and moisture separators condition the compressed air by removing moisture that can cake media. Aerated regulators and vibrating screens keep fine and lightweight media flowing smoothly through the system. Magnetic separators remove ferrous particles that may harm the workpiece.

Manual turntables facilitate handling of heavy, bulky, or delicate parts. Stationary low-profile designs make it easier to access the full height of the workpiece as it rotates. Turntables can also be situated on carts to move a heavier part into and out of the cabinet.

Automation packages may consist of powered rotary turntables, multiple blast guns, oscillating movement for the blast guns, and timer controls. They cover more area faster, enable the operator to perform other tasks, and often increase part-to-part consistency.

Ergonomic designs are relatively new to the market. They conform the machine to the operator, rather than the other way around. Blast cabinet operators can therefore perform at peak efficiency longer and turn out higher quality finishes because distractions have been eliminated. Common ergonomic modifications include a "sit-down" cabinet, padded arm rests, a positionable foot rest, and sound-suppressing devices.

Custom modifications build the machine around a particular part or process. For example, an extra tall part may require a higher cabinet ceiling and two operator positions to allow access to the full height of the part. The same part may be conveyed around the plant on an overhead monorail, so an overhead cable slot may be cut into the roof of the cabinet.

Automatic Blast Systems

Automatic blast systems can increase production and part-to-part consistency when the expense can be justified. They are dedicated to a single workpiece or family of parts. The basic elements of an automated system include material handling (conveyor, rotary, indexing satellites), fixturing, blast (suction or pressure, multiple-oscillating guns), dust collection, media conveying and conditioning, and controls.

Wheel Blast

Mechanically propelled blasting machines differ from air-blast systems in that they apply the media to the workpiece by centrifugal force from a power-driven, high-velocity bladed wheel. They also lend themselves to automatic and semiautomatic production techniques.

Cabinet mechanical blast finishing is the most common, but tumbling equipment is also used. The wheel is enclosed in a protective housing, so there is no danger of stray abrasives. Considerable wear can be expected; therefore, the parts are designed for ease of replacement. Heavy rubber mats are also used to pad worktables and prevent damage from abrasive shot.

Wheel blast equipment covers a wider blast swath and can impact harder than air-blast equipment. Media used are usually limited to steel shot and steel grit because they are durable, less erosive to the equipment, and have maximum "throw weight."

Wet Blast

Wet blasting is a precision finishing operation. It normally consists of an air-blasted slurry of fine abrasive suspended in chemically treated water. Wet blasting can be controlled to avoid metal removal and hold dimensional tolerance to within 0.0001 in. It is also used to hone multitooth hobs and finish fragile items such as hypodermic needles.

Wet-blasting equipment usually incorporates a cabinet. It is frequently modified with auxiliary strippers, take-off conveyors, and wash-rinse-dry stations.

Although wet blasting is usually reserved for small, delicate workpieces, it can be used to remove light surface residues, blend scratches, and correct other surface defects on large pieces. In addition, wet blasting is used to reveal scores, heat-checks, porosity, or metal fractures to determine whether any particular operation has damaged the part.

Abrasive Jet Machining

Abrasive jet machining (AJM) is a specialized form of blast finishing. In this system, a highly controllable precision tool is used to cut, abrade, frost, polish, or peen very hard materials. Examples of such hard materials include ceramics, glass, and germanium.

With AJM, operators are able to cut a 0.0005-in.-thick sheet of tungsten without cracking or splitting the sheet. It can also allow blast finishers to mechanically roughen the surface of a 3-mm-thick germanium Hall-effect device to ensure maximum electrical conductivity. Abrasive jet machining makes frosting glass, microdeburring, and cutting thin precise grooves in bearings possible.

The abrasive particles used in AJM may be as small as 10 μm in size; the nozzle opening could be only 0.0002 in^2. In the process, the media is fed from a reservoir into a high-speed gas stream, which then propels the particles with explosive force. This force sends the media against the surface to be treated at high velocity. The action is shockless, and any heat generated is dissipated by the enveloping gas stream.

MEDIA

The media used in blasting varies greatly in material, size, and shape. This is key to the versatility of blasting. Dry blasting employs abrasive and nonabrasive particles of 12- to

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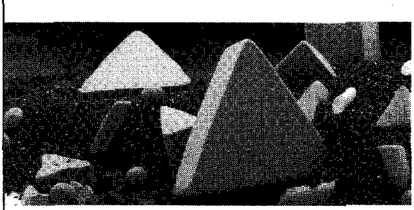

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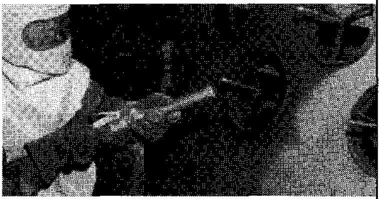

Washington MIlls also offers immediate availability of "BLASTITE BT" abrasive – a sharp cutting abrasive for wet or dry pressure blast cleaning of castings, rust, mill scale, engine overhaul, glass etching, matte finishing and anchor patterning. Tough, durable, BLASTITE is available in a full range of grit sizes.

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300-gauge mesh; wet blasting particles vary from 60- to 5,000-gauge mesh. Particles smaller than 300-gauge mesh can be used in dry blasting, but special handling systems are required.

When considering different media, keep these factors in mind:

Suitability for the purpose—density, shape, hardness
Working speed
Reusability, breakdown percentage
Dust levels generated by broken media
Probability of surface removal for close tolerance parts
Possibility and consequences of substrate contamination
Equipment modifications
Disposal

Glass bead is the most common medium and is often used as an all-purpose media for general cleaning and finishing, including contaminant, coating, or burr removal; honing, blending, and peening. Weld and solder flaws can be detected with glass beading. Glass beads are noncontaminating, leave dimensions unchanged, and are available in the widest variety of sizes. Further information on glass beads is found in the section "Impact Blasting with Glass Beads" elsewhere in this *Guidebook.*

Steel shot is another commonly used media. It is a solid, round particle that causes a peening action and produces a dimpled surface. Steel shot has a relatively high mass, which gives this media greater impact and a hammering action.

Steel grit is an angular product that acts like thousands of tiny chisels. Steel grit cleans quickly and efficiently and produces an excellent surface to which almost any new coating can adhere.

Aluminum oxide is widely used as a cutting media. This substance can produce an anchor pattern in preparation for a new coating. It can also remove heavy foreign matter, deburr, frost or decorate glass, and letter on stone. Aluminum oxide is economical because it can be used over and over again. It is classified in various sizes for a wide selection of finishes.

Silicon carbide is similar to aluminum oxide, but is especially useful for cleaning very hard surfaces, such as tungsten carbide. Silicon carbide is a sharp media that is extremely fast cutting.

Garnet is manufactured from the natural mineral. It, too, is hard and fast cutting. It is used to remove heavy material such as rust and weld scale and leaves a uniform anchor pattern.

Plastic media are relatively soft and gentle. They are most often used for paint removal from delicate substrates such as aircraft, fiberglass and automobiles. Plastic media are also used to deflash molded parts and for cleaning precision molds, dies, electronic connectors, and circuit boards. They can deburr soft materials such as aluminum.

Agricultural media, such as walnut or pecan shells and corn cob, are soft enough to remove foreign matter without etching, scratching, or marring the cleaned areas. They find use cleaning molds, electric motors, and windings.

Two newer media are *wheat starch* and *sodium bicarbonate* (baking soda). Wheat starch can replace plastic for paint removal. Sodium bicarbonate is a water-soluble medium that is convenient for cleaning contaminated surfaces as well as for stripping paint. Sodium bicarbonate requires a flow agent to work reliably, and the large volume of dust generated must be suppressed. Both are soft, low-aggression media that are unlikely to damage parts.

Sand has lost favor to longer life, less dusty, and more versatile media. Silica sand dust has also been found to cause health problems such as silicosis. Alternative media should be explored for anyone still using sand abrasive.

Table I. Pressure Blast Air Requirements (scfm)

Pressure (psi)	*20*	*30*	*40*	*50*	*60*	*80*	*100*	*120*
⅛-in. nozzle	6	8	10	13	14	17	20	25
3⁄16-in. nozzle	15	18	22	26	30	38	45	55
¼-in. nozzle	27	32	41	49	55	68	81	97
5⁄16-in. nozzle	42	50	64	76	88	113	137	152
⅜-in. nozzle	55	73	91	109	126	161	196	220

Table II. Suction Blast Air Requirements (scfm)

Pressure (psi)	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
¼-in. nozzle, 3⁄32-in. air jet	6	7	8	10	11	12	13	15
¼-in. nozzle, ⅛-in. air jet	10	12	15	17	19	21	23	26
5⁄16-in. nozzle, 5⁄32-in. air jet	15	19	23	27	31	37	38	42
7⁄16-in. nozzle, 7⁄32-in. air jet	31	38	45	52	59	66	73	80

BLAST PRESSURE

The correct blasting pressure (psi) and impact angle must be determined to achieve the best possible blasting results. Correct pressure selection will also make any blasting operation more cost efficient. See the air charts in Tables I and II.

Direct pressure uses compressed air more efficiently, so anyone currently blasting with a suction gun at 100 psi may get the same results faster using 60 psi with direct pressure. As shown in the tables, less air volume (scfm) is used for the given unit of work produced, making direct pressure more economical in the long run.

Additionally, the use of excessive pressure only accelerates the breakdown of the media with minimal decrease in blasting time. For example, blasting at 100 psi may reduce the time cycle by 5% as compared to blasting at 60 psi, but the abrasive may break down at a 50% higher pace.

Pressure selection must also take the type of media into account. For instance, if intricately designed jewelry is to be blasted, a fine abrasive with a soft texture would be used at a pressure of 10 to 15 psi. On the other hand, the removal of scale from steel castings could require a coarse, hard abrasive and an air pressure of 80 to 100 psi.

The next variable to be considered is the blast angle vis-a-vis the workpiece. If using aluminum oxide at a 45° angle, maximum scuff, cut, and roughness result. This may be fine if blasting is performed for adhesion or bonding operations; however, if the finest surface finish and the widest possible blast pattern are required, the aluminum oxide should be blasted at a 30° angle. This will produce a smoother scuff pattern.

The distance from the nozzle to the part being blasted should remain constant throughout the process, but this distance may vary from project to project. When synthetic abrasives are used, the recommended distance is 6 to 12 in. More distance is required for heavy ferrous metal media. Softer, natural media should be blasted from a distance of 3 to 6 in., depending on the action needed. Lightweight particles are expelled with more momentum from a direct pressure nozzle and retain their energy component over a much greater distance. For blasting at distances over 12 in., a direct pressure system is by far the most effective.

IMPACT BLASTING WITH GLASS BEADS

by Robert C. Mulhall and Nicholas D. Nedas

Potters Industries Inc., Valley Forge, Pa.

Glass beads were originally used for decorative applications. Their use as a medium in impact blasting came about largely as a result of the aerospace buildup of the 1950s. At that time, a need developed for multipurpose media that combined the advantages of coarse, organic, metallic, and fine angular abrasives. Table I shows a comparison of glass beads with other impact abrasives for cleaning, finishing, peening, and deburring applications.

Impact blasting with glass beads is well placed to satisfy demands of the 1990s for an energy-efficient and environmentally acceptable method of metal finishing. When properly controlled, the system is safe for workers and spent media presents no disposal problems.

PROCESS BENEFITS

Glass beads are virtually chemically inert. This factor, combined with their spherical shape, provides several key benefits. Media consumption is minimized; Table II compares consumption data of impacting media on different metal surfaces of varying hardnesses. On both metals tested, glass beads offer the lowest consumption per cycle. In addition, close tolerances are maintained and glass beads remove a minimal (if any) amount of surface metal.

Impacted surfaces are free of smears, contaminants, and media embedments; high points are blended and pores sealed. A wide range of finishes from matte to bright satin are achievable. The peening action of the media further acts to impart a layer of compressive stresses on the surface of the part. This increases fatigue life, decreases susceptibility of the part to stress corrosion, and enhances surface strength.

PROCESS ENGINEERING

Proper design of impact blasting equipment is essential for each application to achieve the full benefits of high productivity and low costs. Most important, the system should be easily controllable to produce consistent results.

Key to this control is determination and maintenance of the "arc height peening intensity" of the operation. To measure the peening intensity in a particular application, special steel strips are bombarded on one side only by the blasting media. The compressive stress induced by the peening action causes the strip to bow in the direction of the blast. A series of values of arc height versus blasting time are obtained, and when plotted on a graph, yield a saturation curve. From this curve, the arc height peening intensity can be obtained.

Environmental factors, operator skill, OSHA standards, and equipment capabilities are the process parameters involved in all glass bead blasting operations—whether they are cleaning, finishing, peening, or deburring. Once all the variables are optimized and the arc height peening intensity determined, process control is achieved by maintaining that arc height peening intensity. Any change indicates some modification in the system operation, away from optimum performance.

System control via arc height peening intensity is applicable to all cleaning, finishing, peening, and deburring operations. In cleaning, the arc height technique can be used to maintain process speed. In finishing, profilometer measurements of root mean square (rms) microinch finish can be correlated to peening intensity, thereby eliminating any subjective evaluation of performance. In peening, the degree of compressive stress induced is directly

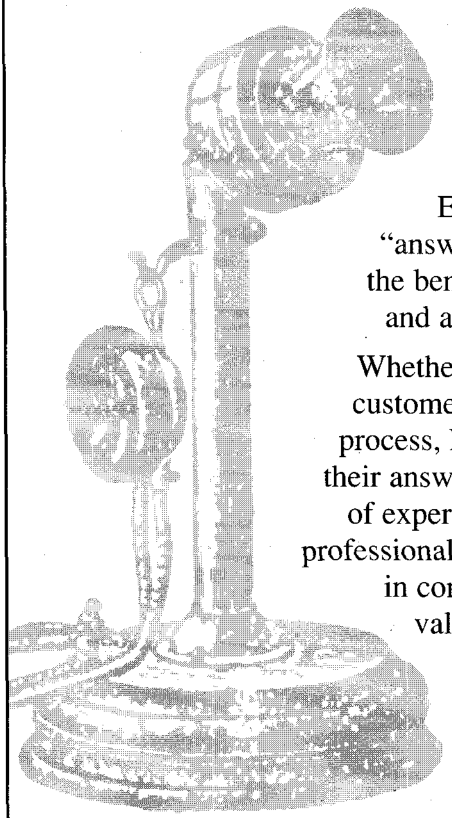


Table I. Impact Media Comparison Chart

	Glass Beads	*Coarse Abrasives (e.g., sand)*	*Metallic Abrasives (e.g., steel and iron shot/grit)*	*Fine Angular Abrasives (e.g., aluminum oxide)*	*Organic Abrasives (e.g., walnut shells)*
Applications:	Cleaning, finishing, peening—light–medium, and deburring	General cleaning where metal removal and surface contamination are not considered	Rough general cleaning and high intensity peening	Cleaning where smooth finish and surface contamination are not important	Light deburring and cleaning of fragile items
Physical Properties:					
Shape	Spherical	Granular	Spherical/irregular	Angular	Irregular
Color	Clear	Tan	Gray	Brown/white	Brown/tan
Specific gravity	2.45–2.50	2.4–2.7	7.6–7.8	2.4–4.0	1.3–1.4
Free silica content, %	None	100	None	<1	None
Free iron content, %	<1	<1	95–100	<1	None
Hardness (Moh)	5.5	7.5	7.5	9.0	1.0
Media Comparisons:					
Toxicity	None	High	None	Low	Low/none
Metal removal	Low/none	High	High/medium	High	None
Cleaning rate	High	Fast	Medium/high	Fast	Slow
Peening ability	High	None	High	None	None
Finish achieved	Range (various matte)	Rough anchor	Peened (shot): rough anchor (grit)	Various matte	Smooth
Surface contamination	None	High	High/medium	High	Medium/high
Suitability for wet blasting	High	Low	Low	Low	Low
Suitability for dry blasting	High	High	High	High	High
Size ranges available	20–325 U.S. mesh	8–200 U.S. mesh	6–200 U.S. mesh	80–325 U.S. mesh	60–325 U.S. mesh
Consumption rate	Low	High	Low	High	High
Cost comparison	Medium	Low	High	High/medium	Medium/low

Table II. Consumption Studies of Various Impacting Media Direct Pressure Dry Blasting System

Blasting Material	*Target Material*	*Hardness, Rockwell*	*Average Consumption per Cycle (%)*
Glass beads (106–153 μm)	Al 2024	75B	2.1
	Al 2024	75B	
	CRS	30C	3.5
	CRS	30C	
Aluminum oxide (180 grit)	Al 2024	75B	6.0
	Al 2024	75B	
	CRS	30C	6.7
	CRS	30C	
Soda-lime silicate ground glass (125 μm and finer)	Al 2024	75B	10.6
	Al 2024	75B	
	CRS	30C	12.9
	CRS	30C	
Borosilicate ground glass (125 μm and finer)	Al 2024	75B	11.4
	Al 2024	75B	
	CRS	30C	13.9
	CRS	30C	

CRS = cold-rolled steel.

3⁄16-in. I.D. nozzle; 1⁄8-in. I.D. grit stem; 90° target angle; 6-in. target distance; 0.006 Npeening intensity; and 25 psi blasting pressure.

related to the arc height peening intensity. By such control, significant benefits are achieved in terms of labor productivity, reduced supervision requirements, and decline in the number of rejected parts.

As indicated in Table I, both steel shot and glass beads are available for peening applications. Steel shot with its heavier density offers a deeper depth of compression, but requires more energy to propel while leaving dissimilar metallic smears (i.e., various forms of contamination) on the part's surface. Glass beads are often used as a secondary peening medium, removing contamination while improving surface texture and finish (lower rms) of the part.

Glass beads are also used extensively as a peening medium, achieving a wide range of arc height peening intensities in a variety of applications and industries (see Fig. 1).

Typical glass bead peening applications take place before plating and after grinding and welding on aerospace, automotive, and machine tool components.

KEY FACTORS IN USE OF GLASS BEADS

There are a few key considerations that will help the user to enjoy the benefits of glass bead impact media to the fullest.

Whether for cleaning, finishing, peening, or deburring, the work actually done depends upon the amount or weight of abrasive thrown against the target surface in a given time. It also depends upon the speed with which the material is thrown against the target. The formula:

$$I = MV^2/2$$

indicates that impact energy (I) equals one half the mass or weight (M) times the square of the velocity (V) at a 90° nozzle angle. Correction factors should be used for other angles.

As a general rule, the smallest particle that will provide the desired effect on the surface is the most efficient one to use, as this gives the greatest number of impacts per pound of glass spheres.

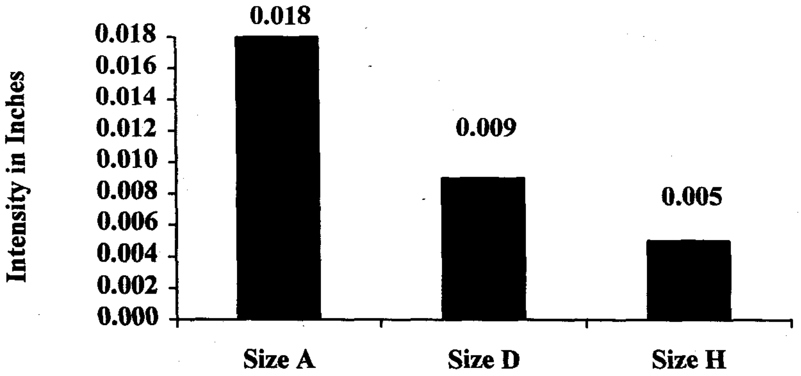


Fig. 1. Typical peening intensities achieved with solid glass beads using suction-type equipment with ½-in. diameter nozzle at 90° for A and H, and 85° for D.

When the nozzle is at a 90° angle to the surface being treated, the bounceback of beads has a "blinding" effect. This interferes with the effectiveness of the blast stream and tends to increase the rate of bead consumption through breakage. Generally, an angle between 45 and 60° will give the most effective performance. In some cleaning applications, still lower angles may help speed the work.

The work energy of the flying particles is also affected by the distance from the nozzle to the work surface. It is usually best to keep this between 4 and 8 in. to avoid loss of velocity, and to gain maximum acceleration and proper diffusion of particles into the most desirable pattern.

BEAD CONSUMPTION

Because beads can become broken after repeated impacts on the work surface, controlling bead consumption is of critical importance. It is affected by five key factors:

1. *Bead size*—the larger the bead, the more durable and resistant to breakage it is at a given impact intensity. This preference for larger beads must be balanced against the greater efficiency of smaller size beads, which are capable of the work required.
2. *Uniformity of size*—proper sizing also affects efficiency of operations. The wider the range of bead sizes in a particular "charge," the higher the rate of consumption at given conditions.
3. *Roundness or sphericity of beads*—the more spherical the individual beads, and the freer the "charge" from nonspherical particles, the lower the rate of bead consumption.
4. *Surface hardness of material being treated*—the harder the surface being treated, the higher the rate of bead consumption.
5. *Angle of impingement*—the closer to 90° the stream of beads is to the work surface at a given arc height peening intensity, the greater the rate of bead consumption.

APPLICATION NOTES

Cleaning

Because of the wide variety of different materials that must be removed in cleaning operations—including mill scale, rust, carbon buildup, and the like—it is often best to experiment with different nozzle angles to find which works most efficiently. Where there are internal recesses and other difficult areas, the use of the smaller bead sizes may be particularly helpful. Because a high cleaning speed usually minimizes labor cost, bead size and nozzle angle are the key considerations. Normally, a velocity that optimizes cleaning speed with a given size of bead will optimize consumption, to give the lowest total cost.

Finishing

Where appearance is of prime importance, bead size is normally the key consideration. Velocity, nozzle angle, and other factors should be adjusted, first to give maximum finishing speed, and second, to minimize consumption. This will provide the lowest total labor and material cost per unit of production. As a general rule, large beads at high intensities provide a deep matte; at low intensities large beads give a smooth, bright surface; small beads at high intensity give a dull matte, and at low intensities a bright satin. Selective masking of surfaces, the use of multiple nozzles, and a "painting" motion may be employed for highly specialized decorative effects. Automated machines are generally used for finishing.

Peening

Peening to increase fatigue resistance or to increase stress corrosion resistance is essentially a uniform "hammering" operation. Uniformity of bead size and control of the number of nonround and angular particles included is critical to process performance. The key consideration is impact intensity, which must be specified as minimum and maximum. Nozzle angles should be as close to a right angle as possible without excess bead consumption. In general, the larger bead sizes, because of their resistance to breakdown, will prove most cost effective. In peening fillet areas, it is a standard rule that beads no larger than one half the radius should be used.

Deburring

The key considerations in deburring are usually a combination of programming surface finish, while achieving sufficient impact intensity to remove or depress the burr. Bead size, which governs finish, must be adjusted to an adequate peening intensity with velocity. Proper nozzle angle will optimize consumption.

MASS FINISHING PROCESSES

by David A. Davidson

Turbo-Finish of America Inc., Bartlett, N.H.

WHAT IS MASS FINISHING?

Mass finishing is a term used to describe a group of abrasive industrial processes by which large lots of parts or components made from metal or other materials can be economically processed in bulk to achieve one or several of a variety of surface effects. These include deburring, descaling, surface smoothing, edge-break, radius formation, removal of surface contaminants from heat treat and other processes, preplate and prepaint or coating surface preparation, blending in surface irregularities from machining or fabricating operations, producing reflective surfaces with nonabrasive burnishing media, refining surfaces, and developing superfinish or microfinish equivalent surface profiles.

All mass finishing processes utilize a loose or free abrasive material referred to as media within a container or chamber of some sort. Energy is imparted to the abrasive media mass by a variety of means to impart motion to it and to cause it to rub or wear away at part surfaces. Although by definition, the term mass finishing is used generally to describe processes in which parts move in a random manner throughout the abrasive media mass, equipment and processes that utilize loose abrasive media to process parts that are fixtured come under this heading also.

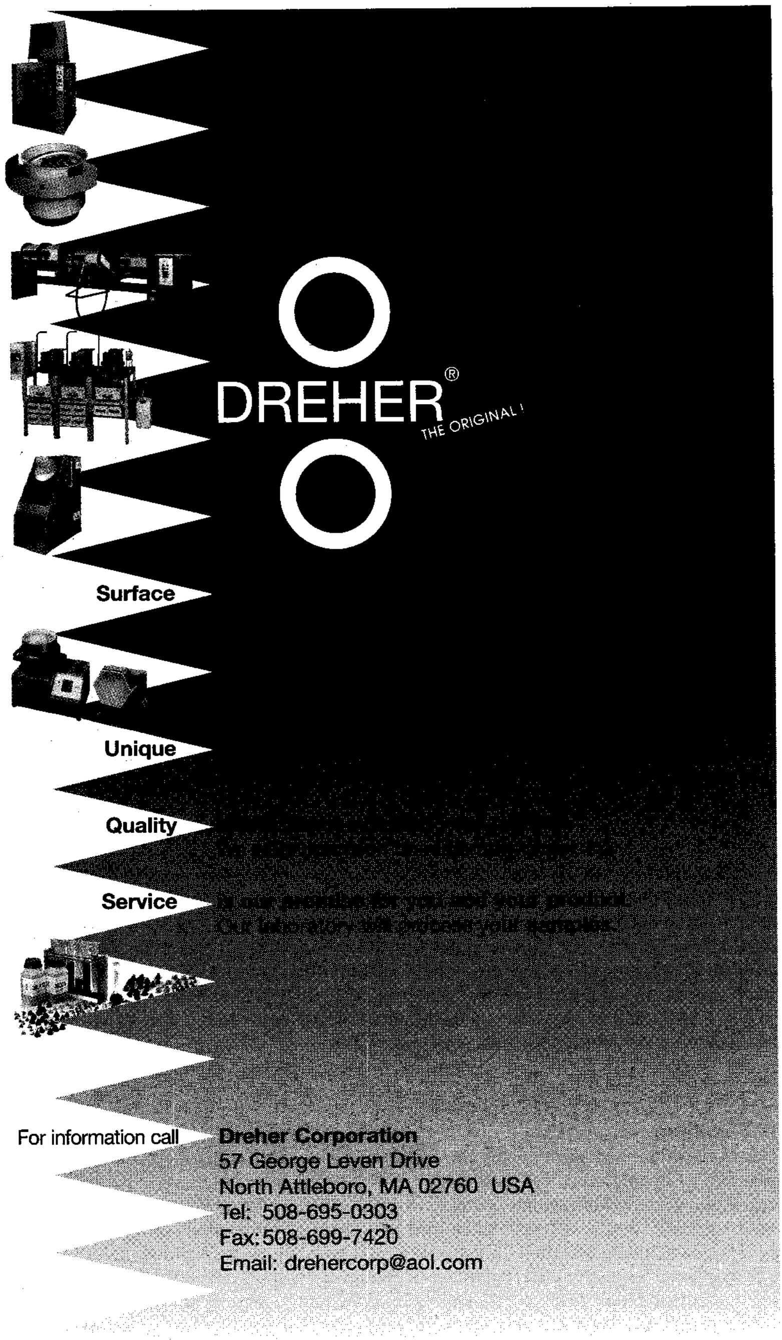
WHY MASS FINISHING?

Nearly all manufactured parts or components require some measure of surface refinement prior to final assembly, or the final finish or coating required to make the parts acceptable to the consumer or end-user. Most manufacturing companies who employ mass finishing techniques do so because of the economic advantages to be obtained, especially when compared with manual deburring and surface finishing techniques. Mass finishing processes often reduce or eliminate many procedures that are labor intensive and require extensive part handling. This is especially important in meeting increasingly stringent quality control standards, as most mass finishing processes generate surface effects with part-to-part and lot-to-lot uniformity that cannot be replicated with processes in which parts are individually handled. It has become a manufacturing engineering axiom that part reject and rework rates will plummet, if a mass finishing approach can be implemented to meet surface finish requirements.

Although each of the mass finishing process types carries with it a unique set of process strengths and weaknesses, all of them are sufficiently versatile to be able to process a wide variety of part types successfully. A plethora of abrasive media types, sizes, and shapes makes it possible, in many cases, to achieve very different results within the same equipment, ranging from heavy grinding and radiusing to final finishing. Components from almost every conceivable type of material have been surface conditioned using mass finishing techniques including ferrous and nonferrous metals, plastics, composition materials, ceramics, and even wood.

MASS FINISHING CAUTIONS

Despite the immense versatility of these types of processes, some potential process limitations should be noted. It can be difficult to selectively treat certain part areas to the



exclusion of other areas, which might have critical dimensional tolerance requirements. Unless masked or fixtured, all exterior areas of the part will be affected by the process to a greater or lesser degree, with effects on corners and edges being more pronounced than those on flat areas, and with interior holes, channels, and recesses being relatively unaffected in the more common processes.

Care must be exercised in media size, shape selection, and maintenance to prevent media lodging in holes and recesses, which might require labor-intensive manual removal. Some parts have shapes, sizes, or weights that may preclude them from being finished in some mass finishing processes because of the risk of impingement from part-on-part contact or of nesting due to certain features of the parts interlocking together when in proximity. Additionally, most processes that use water in conjunction with the abrasive media create an effluent stream, which must be treated prior to discharge into municipal sewage or other disposal.

MASS FINISHING—PART OF THE MANUFACTURING PROCESS

Much time and money can be saved both in mass finishing process operations and in process development if finishing considerations are given sufficient weight at the design, production, and quality control stages. Although it is a rule more breached than observed, it should be noted that mass finishing processes are not, and were never intended to be, methods for rectifying errors made in earlier stages of the manufacturing process. It should be equally obvious that processes developed for parts made with tools and dies that are sharp will no longer produce the same results when that tooling becomes dull. Mass finishing processes can produce remarkably uniform results if process parameters are followed carefully, but this assumes some measure of uniformity of surface condition for a given part within a lot, and from lot-to-lot, as received in the finishing area.

MASS FINISHING EQUIPMENT

One of the more obvious factors influencing mass finishing processes is equipment selection. There are five major equipment groups as follows: barrel, vibratory, centrifugal barrel, centrifugal disk, and spin/spindle finishing.

As Table I shows, there are variations within each major grouping, and each equipment group has its own set of advantages. The first four groups are primarily used with parts immersed within a body of abrasive media and are capable of some independent movement within that mass. On occasion, fixturing or some subcompartmentalization may be used to isolate delicate or critical parts from each other. Part-on-part contact may also be minimized by using higher media-to-part ratio combinations. Common media-to-part ratios for noncritical parts run anywhere from 1:1 to 1:4 by volume. Parts with a higher need for cushioning and protection may utilize media/part ratios as high as 10:1 to 15:1. In contrast, all spin/spindle finishing processes utilize fixturing of parts, and in most cases movement of the fixture develops much of the action needed to abrade the parts.

Barrel Finishing

Barrel finishing is unquestionably the oldest of the mass finishing methods, with some evidence indicating that crude forms of barrel finishing may have been in use by artisans as far back as the ancient Chinese and Romans as well as the medieval Europeans.

In this method, action is given to the media by the rotation of the barrel. As the barrel rotates, the media and parts within climb to what is referred to as the turnover point. At this point, gravity overcomes the cohesive tendencies of the mass, and a portion of the media mass slides in a retrograde movement to the lower area of the barrel. Most of the abrading or other work being performed on parts within the barrel takes place within this slide zone, which may


A big step for
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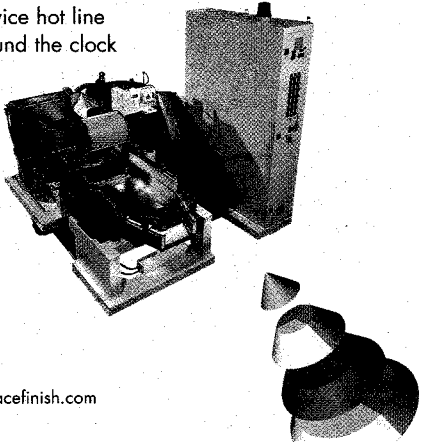


Table I. Mass Finishing Equipment Selection Considerations

	Horizontal Barrel	*Oblique Barrel*	*Round Vibrator*	*Tub Vibrator*	*Centrifugal Barrel*	*Centrifugal Disk*	*Spin/Spindle Finish*
Time cycles	Long	Longer	Medium	Medium	Short	Short	Very Short
Media wear	Slow	Very slow	Moderate	Moderate	High	Very High	Very High
Media size	Large	Large	Medium	Medium	Small	Small	Very small
Equipment cost	Low	Low	Moderate	Moderate	High	High	High
Typical kinds of processes	Heavy radiusing, burnishing, dry polishing	Drying, part-on-part finishing	Deburring, smoothing, burnishing, preplate	Deburring, stock removal, large parts	Microfinishing, polishing, fast stock removal	Aggressive stock removal, smoothing, deburring	Aggressive deburring, stock removal, no impingement, dry color buff
Part size limitations	Medium	Small to medium	Restricted length by bowl diameter; flat parts nest	Almost unlimited, very large—one per machine	Small to moderate, fixturing or compartments possible	Part length severely restricted by size of chamber	Some part geometry restriction
Type of energy	Rotational, gravity slide	Rotational, gravity slide	Kinetic, vibratory	Kinetic, vibratory	Centrifugal, pressure	Centrifugal, toroidal	Spin, media resistance
Continuous or batch	Batch	Batch	Continuous possible	Continuous possible	Batch	Batch	Batch
Liquid compound usage	Low	Low	High with flow-through systems	High with flow-through systems	Low	High with flow-through systems	Medium
Working capacity	50%	35%	80–90%	80–90%	60% wet, 80–90% dry	30–40%	N/A; Fixtured
Exterior or interior part areas	Concentrates on exterior corners, edges	Concentrates on exterior corners,edges	Interior and exterior	Interior and exterior	Exterior; some interior	Exterior and interior similar	Dependent on fixture orientation
Media/parts material handling	Awkward with external separation	Easier unloading than horizontal barrel	Automated internal separation	Discharge chute to exterior separation	Manual load, machine unload	Manual or automatic	Manual or robotics
In-process inspection?	No	Yes	Yes	Yes	No	Yes, usually	Not usually

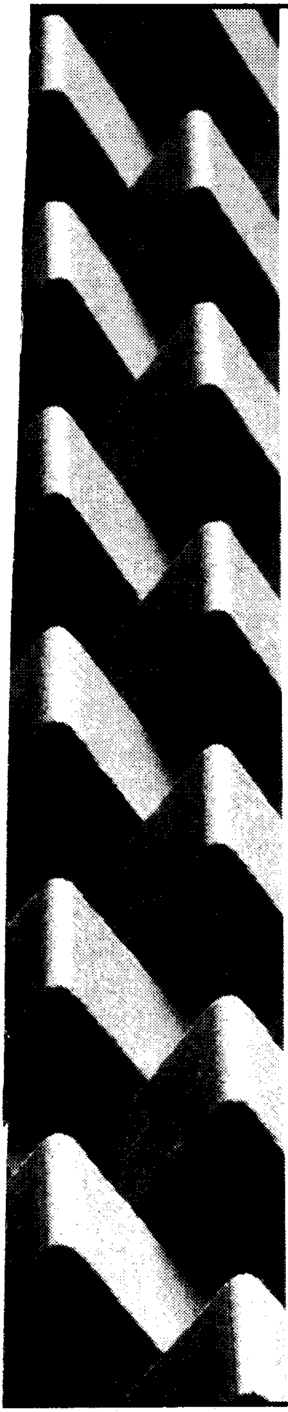


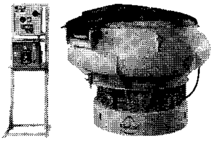
Table II. Barrel Processing Variables

Barrel Processing Condition	*Process Effect*
Media/parts fill level too low (Fill level well below the 50% mark)	Reduced length of slide zone, usually insufficient cushioning and protection of parts, slower cycle times with possibility of rougher finish and potential for part damage
Optimum media/parts fill level (50–60%)	Longest possible slide zone, abrading efficiency considered to be at maximum
Media/parts fill level too high	Restricted slide zone with increased time cycle. May be desirable for processing delicate parts, which require more cushioning and slower media action.
Media size and abrasive content	Larger media and coarser abrasive content will perform deburring and develop generous radii rapidly but will generate less refined surfaces. Smaller media and finer abrasive grit will produce more refined finishes.
Water level	As a general rule, water levels are kept close to the top of mass, higher levels will retard movement and generate more refined finishes, low levels may accelerate movement and create rougher surface finishes.
Rotational speed	Movement within the barrel is usually measured in surface feet per minute (sfpm) The optimum speed for deburring operations is usually 100–200 sfpm, where burnishing operations are usually performed in 40–90 sfpm range. A 30-in. barrel will achieve 180 sfpm if rotated at 24 rpm, and will produce 60 sfpm at 8 rpm. Rotational speeds faster than these norms may cause parts to cascade outside the media mass. Excessively slow speeds lengthen time cycles.
Compound	Many barrel finishing compounds have high foaming characteristics. The foam fills the upper area of the barrel and often acts as a buffer or cushion, which curbs the action inside the barrel. In some barrel processes, the barrel contents will be rinsed and a new compound added, which will change the nature of the process, allowing for a two-stage process in the same equipment.

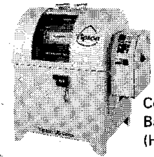
involve as little as 10–20% of the media mass at any given moment. A variety of process elements may have an effect on this slide zone and its efficiency. Some of these are noted in Table II.

Tumbling barrels are available in a variety of configurations, the most common being a horizontally oriented octagonal chamber, which provides a much more efficient media lift than a purely cylindrical shape. Other configurations include barrel chambers mounted on pedestals, barrels with front or end loading, perforated barrels encased in a water tank or tub, and so called triple-action polygonal barrels. Also used extensively are oblique barrels, similar in some respects to small batch concrete mixers. This equipment is used for light deburring and finishing as well as part drying. It has the advantage of permitting operator inspection while in process, and its open end can be tilted down for ease of unloading, but it is much less efficient than horizontal equipment, and suffers from the tendency of parts and media to segregate in extended time cycles.

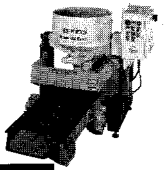
As is the case with most other mass finishing equipment, polyurethane, rubber, or linings made from similar material are used to extend equipment life, provide some measure of cushioning to parts, and furnish some measure of noise abatement. Although considered by some to be an outdated and obsolete finishing method, barrels still have a place in the finishing engineer's repertoire. Although it is true that it is slower and presents some automation and materials handling challenges, it is sufficiently versatile to perform numerous finishing operations for many manufacturers. Furthermore, barrel finishing provides an excellent alternative for flat parts, which may nest in vibratory systems. Although perhaps



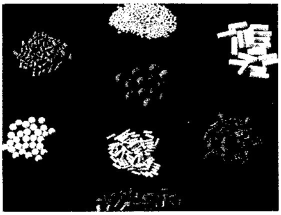
High-Energy Vibratory Bowl (CLS-600)



Centrifugal Barrel (HS-R30X)



Centrifugal Disc (EFF-105-SA)



requiring some measure of operator experience in order to be used effectively, barrel finishing is capable of producing some unique and desirable surface finishes and is highly efficient in compound and media usage.

Vibratory Finishing Systems

Vibratory finishing was introduced during the 1950s and, through a succession of design refinements, has become the primary workhorse of the industry. Equipment usually consists of a spring-mounted open chamber, lined with polyurethane or similar material, to which a vibratory motion generator is attached. The motion generator is usually mechanical in nature, consisting of a rotating shaft with eccentric weights affixed. (A few machines make use of electromagnetic motion generators.)

The motion of the media within the chamber can be controlled by adjusting the speed of rotation (frequency ranges between 900 and 3,000 rpm, more commonly between 1,200 and 1,800 rpm), the positioning of the eccentric weights, and the amount of the weight attached (amplitude— the amount of "rise and fall" being imparted to the container and media—can range between 1⁄16 in. [2 mm] to 3⁄8 in. [10 mm]). The actual chambers are available in a variety of shapes (round bowl, oval, or U-shaped tub being the most common.) The adjustments noted above will not only affect the vibratory motion of the media, but the roll or forward motion within the chamber (spiral motion in the case of many round bowls).

A number of advantages have manifested themselves over traditional barrel finishing methods. Unlike barrel processing, the entire media mass is in motion at any given time, so parts are being constantly treated, making for shorter cycle times. The entire chamber is utilized to its full capacity and, in many cases, the vibratory motion of the machine can be harnessed to assist in unloading. Many round bowl equipment designs are capable of internal separation, where an integral separation deck is used to separate and retrieve media from parts being unloaded at the end of a cycle. The open nature of equipment allows for ease of operator monitoring of the process on a continuous basis.

Tub Vibrators

This equipment ranges in size from 1 ft^3 capacity up to 200 ft^3.

Tub vibrators are considered to have more aggressive media action than round-bowl machines, and they are capable of processing very large, bulky parts (as large as 6 ft by 6 ft) or potentially awkward part shapes (parts 40-ft long and longer). The vibratory motion generators consist of rotating shafts with sets of eccentric weights attached either at the bottom of the U-shaped tub or one of the sidewalls.

This equipment is usually loaded from the top of the chamber, and usually unloaded through a discharge door located on a side panel. Parts and media can be screened on an external separation deck. This arrangement allows for relatively quick load/unload or media changeover cycles when compared with other equipment.

Tub-shaped or tubular-shaped vibrators are commonly utilized for continuous high volume applications where the time cycle required to process the parts is relatively short. Media return conveyors and feed hoppers are used to meter the correct ratio of media and parts to the loading area of the machine, while media and parts are separated on a continuous basis by a screen deck located at the unload or discharge area of the machine. Tub-type machinery is also used extensively for batch applications and can be easily subcompartmentalized for parts that require total segregation from each other. A typical machine is shown in Fig. 1.

Round-Bowl Vibratory Systems

Round-bowl equipment normally has a processing chamber that resembles the bottom half of a doughnut. Although up to 20% slower than tub-style machines, and having occasionally more unwieldy media changeover routines, the advantages in automation and

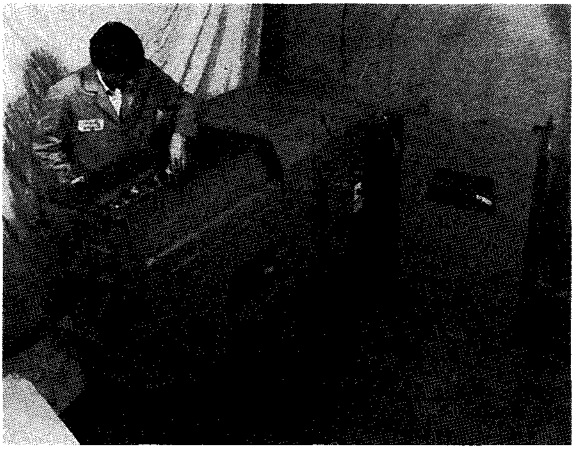


Fig. 1. Tub vibratory machine. Photo courtesy Harper Surface Finishing Systems Inc., Meriden, Conn.

material handling for these machines have often given them an edge in any processing cost per part analysis. The vibratory motion generator on these machines is customarily a vertical shaft mounted in the center-post area of the bowl. Adjustments related to the eccentric weights on this shaft will affect the rolling motion of the media, as well as the forward spiral motion of the media in the bowl chamber. This spiral motion is one of the machine's more salient advantages, as it promotes an even distribution and segregation of parts in the mass, thus lessening the chance of part-on-part contact.

Like tub machines, equipment size varies from small bench models, whose capacity are measured in quarts or gallons, to very large equipment in excess of 100 ft^3 capacities. Successful processing requires appropriate media and compound selection, correct amplitude and frequency adjustments of the motion generator, and precisely determined water flow rate and compound metering rates. Unlike barrel systems, whose water levels are determined once at the beginning of the cycle, vibratory systems have a constant input and throughput of water into the system (both flow-through and recirculation systems are employed, although flow-through is generally much preferred).

Water levels are critical to process success. Too much water will impede the vibratory motion of the mass. Too little will permit a soils/sludge buildup on the media, reducing its cutting efficiency. Flow-through functions can be automated with appropriate controls and metering devices. For parts requiring relatively short cycle times, round-bowl machines can be configured to perform in a continuous mode, the parts being metered in and then making one pass around the bowl, and exiting via the internal separation deck. Some designs include a spiral bottom to enhance loading from the machine onto the separation deck, lessening the likelihood of part-on-part contact at the entrance to the separation deck.

Ease of use and economy are the hallmarks of vibratory finishing methods, and have contributed to making this perhaps the most accepted deburring and surface conditioning method for finishing parts in bulk. The equipment performs well in either batch or continuous applications. Standard applications usually can be run most economically in round-bowl-type equipment. Larger parts may require more specialized tub-type equipment, large volumes of parts, which can be processed in relatively short cycles, can make use of continuous tub or bowl equipment, or even multipath equipment. The latter can offer parts transfer from one operation to a secondary-type operation within the confines of the same machine, but different chambers. Vibratory action itself often will preclude the ability to develop superfinishes or microfinishes. These types of finishes are often best attempted in equipment in which the media action has a more rolling, glancing, or linear action than short stroke movement characteristic of vibratory finishing.

Centrifugal Barrel Finishing

Centrifugal barrel finishing (CBF) is a high-energy finishing method, which has come into widespread acceptance in the last 25–30 years. Although not nearly as universal in application as vibratory finishing, a long list of important CBF applications have been developed in the last few decades.

Similar in some respects to barrel finishing, in that a drum-type container is partially filled with media and set in motion to create a sliding action of the contents, CBF is different from other finishing methods in some significant ways. Among these are the high pressures developed in terms of media contact with parts, the unique sliding action induced by rotational and centrifugal forces, and accelerated abrading or finishing action. As is true with other high energy processes, because time cycles are much abbreviated, surface finishes can be developed in minutes, which might tie up conventional equipment for many hours.

The principle behind CBF is relatively straightforward. Opposing barrels or drums are positioned circumferentially on a turret. (Most systems have either two or four barrels mounted on the turret; some manufacturers favor a vertical and others a horizontal orientation for the turret.) As the turret rotates at high speed, the barrels are counterrotated, creating very high G-forces or pressures, as well as considerable media sliding action within the drums. Pressures as high as 50 Gs have been claimed for some equipment. The more standard equipment types range in size from 1 ft^3 (30 L) to 10 ft^3, although much larger equipment has been built for some applications.

Media used in these types of processes tend to be a great deal smaller than the common sizes chosen for barrel and vibratory processes. The smaller media, in such a high-pressure environment, are capable of performing much more work than would be the case in lower energy equipment. They also enhance access to all areas of the part and contribute to the ability of the equipment to develop very fine finishes. In addition to the ability to produce meaningful surface finish effects rapidly, and to produce fine finishes, CBF has the ability to impart compressive stress into critical parts that require extended metal fatigue resistance. Small and more delicate parts can also be processed with confidence, as the unique sliding action of the process seems to hold parts in position relative to each other, and there is generally little difficulty experienced with part impingement. Dry process media can be used in certain types of equipment and is useful for light deburring, polishing, and producing very refined superfinishes.

Practicality and questions of cost effectiveness often determine whether high-energy methods are selected over conventional barrel or vibratory processes. If acceptable surface finishes can be developed in a few hours, conventional equipment is usually the most economic alternative. CBF equipment's strong suit is the ability to develop surface finishes that may require over-lengthy time cycles in conventional equipment and the ability to develop a wide range of special surface finishes required for demanding and critical applications.

Centrifugal Disk

Another high-energy finishing method that has become popular in recent years is the centrifugal disk. Most equipment is in the form of a cylinder or bowl with a spinning disk at the bottom. This disk propels the media upward against the interior sidewalls of the cylinder, which act as a brake, causing the mass to turn over and return to the center of the disk, where it is set in motion again. This unique media action is said to perform abrading operations at five to 10 times the speed of conventional vibratory action. As the machine is basically an

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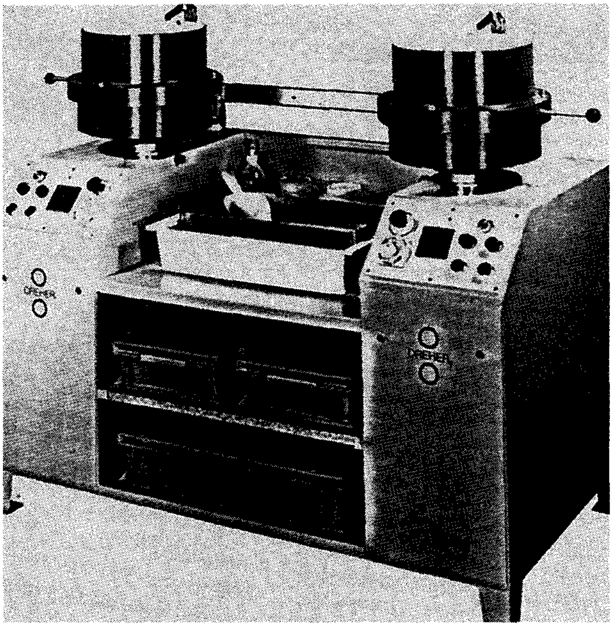


Fig. 2. Centrifugal disk finishing machine for two-step dry processing. Photo courtesy Dreher Corp., North Attleboro, Mass.

open end chamber, in-process inspection and monitoring are possible. Faster time cycles can also reduce work in progress and make the equipment a good choice for manufacturing cells. In general, larger or lengthy parts are not good candidates for disk finishing and, at times, higher than usual media-to-part ratios must be maintained to avert part-on-part contact. Equipment size ranges from ½ ft^3 (15 L) bench-top models to 20 ft^3 (600 L) floor machines.

One critical area of attention on this equipment is the gap between the spinner disk and the ring located around the exterior of the disk. Particles or fines of media that are capable of lodging in this area may cause significant damage to certain types of equipment. Correct media maintenance and attention to water flow-through rates can be an important factor in extending the useful service life of main components. Some equipment has the ability to run either wet or dry process media. Many equipment models, however, are designed for dedicated use in either wet or dry finishing and should not be used in the other mode without extensive consultation with the manufacturer. A two- bowl dry disk finishing system is shown in Fig. 2.

Spin/Spindle Finish Equipment

Spindle finishing is performed by fixturing parts at the end of a (stationary, rotating, planetary, or oscillating) spindle, and arranging for the part to be immersed in a mass of fine media, which may be vibrating, stationary, or directed at the workpiece by a spinner arrangement or rotation of the entire media chamber. As all parts must be fixtured, impingement from part-on-part contact is nonexistent. Time cycles can be very short, ranging from a few seconds to a few minutes. Equipment from various manufacturers may feature single or multifixture capabilities. Types of operations vary from heavy abrasive operations for deburring and stock removal, to the use of very fine dry polishing media in some equipment to develop color-buff-type finishes. One recent development in spindle finishing is the turbofinish method, which involves the high-speed rotation of components in a fluidized bed of fine abrasive or polishing material.

MASS FINISHING MEDIA

Media can be generally defined as the loose material contained in the work area of a mass finishing machine, which, when in motion, performs the work desired on part surfaces. Media may be natural or synthetic, abrasive or nonabrasive, random or preformed in shape. Much of the versatility inherent to mass finishing processes can be traced to the wide array of media types, sizes, and shapes available to industry. What follows is a rundown of the more commonly used media types.

Natural/Mineral Media

Crushed and graded stone was once the predominant source for tumbling abrasives in the early days on barrel finishing. Raw source material included both limestone and granite. Some naturally sourced materials still find some barrel finishing applications today, such as corundum and novaculite. As a general rule, problems with fracturing, rapid wear and attrition rates, lodging, and disposal of the high amount of solid or sludge waste material created mitigates against crushed and graded mineral materials being an effective media for most applications.

Agricultural Media

A variety of granular media such as ground corn cob, walnut shell, pecan shell, sawdust, and wooden pegs are used in all of the equipment discussed. These dry process media are used in conjunction with various fine abrasive compounds similar to compounds that might be used in buffing applications. These media are often used in secondary cycles, after initial cutting and smoothing, to produce very fine reflective finishes. Attractive decorative finishes can be produced for jewelry and other consumer articles and, by extension, very low R_a finishes can be produced for precision industrial components.

Preformed Media

These media have largely replaced the crushed and graded mineral materials mentioned above. Media preforms are made from either extruded ceramic/abrasive shapes, which are fired, or resin-bonded, or which have been molded. The preform concept was an important one for the finishing industry. Unlike the more random shaped mineral media, size and shape preform selection could prevent media lodging and promote access to complex part shapes. The uniformity and predictable wear rates of the media also made it possible to prevent both lodging and separation problems caused by undersized, worn media. A wide variety of shapes have been developed by various manufacturers over the years to accommodate these requirements, including cones, triangles, angle-cut cylinders, wedges, diamonds, tristars, pyramids, arrowheads, and others.

Ceramic media are generally harder and more abrasive and are customarily used for more aggressive applications. Plastic media, as a rule, are somewhat softer and capable of producing finer finishes.

Burnishing Media

Media made from case hardened steel, stainless steel, and other formulations are used widely in barrel and vibratory equipment to produce burnished surfaces. These media are very heavy (300 lb/ft^3 versus 100 lb/ft^3 for ceramic media) when compared with other media types and are nonabrasive in nature. It should be noted that not all vibratory equipment can turn or roll steel media. Because of the weight, enhanced or heavier duty equipment may be necessary. The media performs by peening or compressive action; surface material is not removed, as is the case with abrasive media. Burnishing processes with steel media can be used either to develop reflective decorative finishes or provide functional finishes. One attribute of burnishing processes is that part surfaces are often work-hardened, which can extend the service life of components in moving assemblies. Steel media can be extremely long lasting, if care is taken to prevent corrosion of surfaces while in use and/or storage. Nonabrasive porcelain media are also used for some burnishing procedures and are prevalent in some centrifugal applications.

COMPOUNDS

Many abrasive and burnishing applications use water with specially formulated compound additives. The proper selection and dosage of these additives (in either liquid or dry powder form) can have a critical effect on the viability of the process. These compounds perform an assortment of functions including water conditioning or softening, pH control, oil/soil and metallic and abrasive fine suspension to prevent redeposition on part surfaces, rust inhibition, cleaning, foam development or control, as well as media lubricity control. Some special compounds are used to chemically accelerate finishing cycle times; some of these may be intensely caustic or corrosive and may require some special handling.

CHEMICAL SURFACE PREPARATION

METAL CLEANING

by Robert Farrell and Edmund Horner

Hubbard-Hall Inc., Waterbury, Conn.

Simply stated, the function performed in metal cleaning is removal of material, collected in the previous operations, from the metal's surface to prepare it for subsequent operations.

Cleaning metals involves not only the selection of the type(s) of cleaners, but also the proper cleaning cycle and process equipment necessary to generate acceptable parts at a given rate (parts/hour).

An equation for such a cleaning operation may be illustrated as follows:

Process Equipment + Process Cycle + Cleaner(s) = Acceptable Parts/Hour

Each of the terms in the equation shares the burden in providing acceptable parts at a given rate for an economical operation. The equation also notes that in certain operations more than one cleaner may be required, as per a line for electroplating.

Process equipment is the equipment selected—rack line, barrel line, spiral washer, ultrasonic, etc.

SOILS

Soils are the materials left on the metal's surface from the previous operation(s) or the surface condition of incoming metal stock. Examples of the variety of soils that are encountered in metal cleaning are listed below. There may be instances where more than one soil is present on the part.

Rust
Scale (weld or heat)
Tarnish
Oxides that inhibit subsequent finishing
Smuts
Carbonaceous soils
Drawing compounds
Machining oils
Stamping oils
Spinning lubricants

Fingerprints
Buffing compounds
Polishing compounds
Metallic compounds
Glove prints
Corrosion-preventive compounds
Fluxes from brazing operations
Phosphate coatings impregnated with forming lubes
Corrosion products
Stenciling inks
Burnishing-compound residues
Brightener residues left on the surface from previous plating steps
General shop soils that accumulate during storage

These soils may generally be divided into three categories:

Organic soils are typically the lubricants used in metal forming, rolling, and machining operations. The lubricants may be based upon petroleum or synthetics (water-soluble) formulations. Soaps, lard oils, and wax bases are also encountered.

Inorganic soils include rust, heat and weld scale, smuts, and oxides (tarnish).

Miscellaneous soils include shop dirts, glove prints from handling the parts, fluxes from brazing operations, and burned-on soils from quenching operations.

As a rule soil removal is not a simple reaction, e.g., lard oil reacts with caustic soda to form a soap. The reactions can be somewhat more complex.

An important concern, which adds to the cleaning problem, is the age of the soil. Soils that are allowed to age on the metal surface for an extended time become increasingly difficult to remove. A classic example is aged buffing compounds on zinc die castings. It is important, therefore, to clean parts soon after they arrive from their last operation.

PROPRIETARY CLEANERS

To begin with the concept of one cleaner for all soils and all metals does not exist, although chlorinated solvents have come close to achieving that honor.

Proprietary cleaners fall into the following groups: alkaline (mild to strong); neutral (pH 7.0); acidic (mild to strong); emulsion; and solvent. The physical forms of cleaners on the market may be powder, liquid, or gel.

In the development of a cleaner not only are the soils a consideration but also the base metal to be cleaned. As a rule the cleaner's function is to remove the soil and not have any detrimental effect on the metal's surface. For example, a product containing caustic soda would be satisfactory for cleaning ferrous metals but not for cleaning aluminum alloys, zinc die castings, galvanized stock, or yellow brass. Such a product would attack these nonferrous surfaces. The proper selection of a cleaner for the metal substrate to be cleaned is thus paramount.

The bulk of the proprietary cleaners used in industry fall into the alkaline group. Many solvent cleaners are being phased out because of environmental considerations and other hazards. Acid cleaners generally are used for cleaning stainless steel alloys, wrought aluminum alloys, copper, and brass alloys.

Proprietary alkaline soak and spray cleaners are generally formulated to clean a variety of metal-forming lubricants from a metal's surface, and may also find application for cleaning a variety of metals, i.e., ferrous metals, aluminum alloys, brass, and magnesium alloys.

Within the last three years the development of a new cleaner formulation has become further complicated by environmental restrictions imposed by federal and local regulations and by corporations themselves. For example, a specific requirement given for a spray cleaner was that the product must be safe on most metals within the specific allowed cleaning time, but must also be free of phosphates, silicates, chelators, and nitrites; have a low COD/BOD; and have an operating pH between 8 and 9.

If, for example, some of the restrictions encountered when formulating a cleaner were applied, it would have to have the following characteristics:

Chromate free
Phosphate free
Silicate free
Fluoride free
Chelator free
Nitrite free
Amine free
Low COD
Borate free
Noncyanide
Noncaustic
Solvent free
No foam products
High flash point solvents
Powders or liquids
Low BOD
Emulsifier free
pH of 7.0–9.0

Some of the reasons for these restrictions are self-evident such as cyanide free, solvent free, chelator free, and phosphate free.

From the collection of restrictions given one may readily note that the products of the future must be not only safe to the environment, but also relatively safe to use in the work area, and provide a cleaner that will allow the separation of the soil from the cleaning solution.

PROCESS ALTERNATIVES

The method or combination of methods selected to clean parts is critical and will depend upon the type of final finish (plated, painted, anodized, etc.) and whether it is an in-process cleaning operation, or just a final cleaning. And, of course, the other paramount factor to be considered is the volume of work processed per hour.

The cleaning methods given may be used independently or in conjunction with one another, as in a preplate cleaning cycle, where three to four modes of cleaning are used.

Immersion (Rack or Barrel)

Rack immersion may utilize air agitation or work agitation to improve or shorten the cleaning time. In barrel lines the movement of the barrel will provide the necessary agitation to flush cleaner solution through the parts.

Power, Spray Cleaning

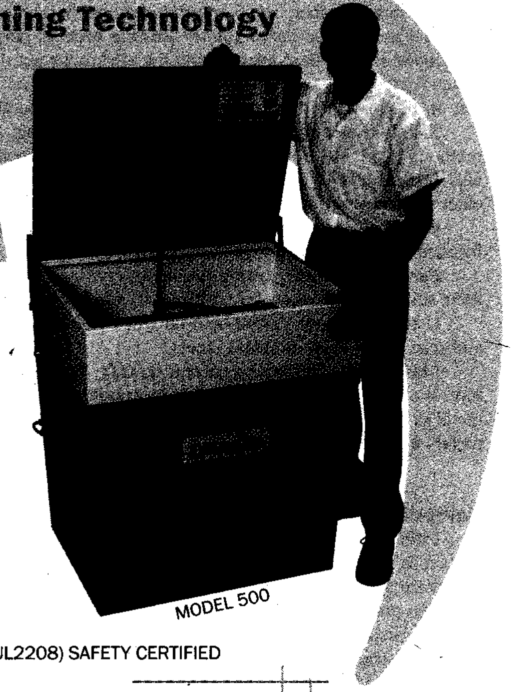
Spray washers (spiral spray, belt washer, spray strip line, cabinet, and monorail-type washer) provide reduced cleaning time by utilizing impingement to clean parts that may not respond to conventional soak cleaning. Spray pressures may range from 14 to 200 psi, depending upon the type of machine used. Some continuous strip spray washers may also utilize rotating brushes along with the spray cleaning solution.

Ultrasonic Cleaning

Ultrasonic energy is utilized in conjunction with aqueous cleaners or hydrocarbon chlorinated solvents to clean parts. Areas of application are small precision parts, parts with complex configurations, removal of tightly adhering or embedded particles from parts, or cleaning parts for hermetically sealed units. One of the key factors in a successful ultrasonic cleaning operation, besides selecting the proper cleaner, is proper racking.

Alkaline Electrocleaning

Alkaline electrocleaners should not be used as the initial cleaner to remove the bulk of soils such as drawing compounds, stamping oils, buffing compounds, machining oils, heavy



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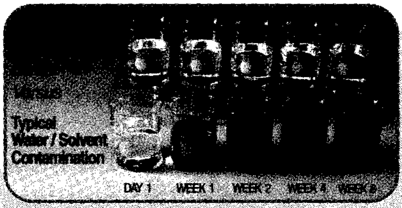

Versus
Typical
Water / Solvent
Contamination
DAY 1
WEEK 1
WEEK 2
WEEK 4
WEEK

Table I. Current Density Ranges for Electrocleaning

Substrate	*Current Density (A/ft^2)*
Ferrous metals	40–150
Copper metal and plate	25–50
Brass alloys	15–40
Zinc die castings	10–30
Nickel plate	20–30
Lead, lead alloys, and pewter	10–30

rust, and weld scales. This function should be reserved for an alkaline soak cleaner, emulsion cleaner, spray cleaner, acids or combinations thereof, which precede the electrocleaner. The electrocleaner is the last alkaline cleaning process performed on the metal surface prior to electroplating. At the point entering the electrocleaner the only soils present should consist of smuts (carbon or iron oxides), light flash rust, light oxides, and residues of soils and cleaners left on the metal surface from the prior cleaning operations.

Alkaline electrocleaning, prior to electroplating, is one of the most reliable cleaning methods available. The cleaning action not only depends upon the cleaner formulation but also utilizes the liberation of oxygen or hydrogen (depending on polarity) formed during electrolysis to scrub residues from the surface.

Of the three electrocleaning methods anodic cleaning is most frequently used, especially for steels and brass and zinc die castings.

Periodic reverse cleaning is usually confined to cleaning ferrous metals, which have as their soils heat scales (weld scale), rust, and smuts.

Cathodic cleaning must be used when electrocleaning nickel, nickel alloys, pewter, lead and lead alloys, and stainless steels.

Maintaining the proper current density, besides operating concentrations and temperature, is a paramount factor that must be maintained in order to obtain the desired results. Each metal is electrocleaned using a different current density range. The ranges for the particular metals are given in Table I.

Cathodic Pickling

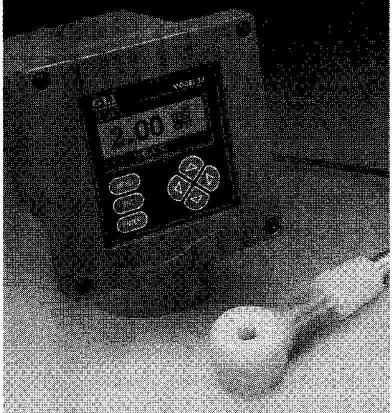
Cathodic electrolytic pickling in an electroplating line is usually confined to the pickling of ferrous metals and activation of nickel-plated surfaces. Electrolytic pickling is another form of electrocleaning, but on the acid side.

The principal functions of an acid solution in an electroplating cycle are removal of rust, scale, tarnish, light oxides, metal slivers, and in some cases, smut. Electrolytic pickling is usually restricted to difficult tasks where the soils are quite heavy or where the allotted pickling time is short. The pickling action, in an electrolytic process, is assisted by the evolution of hydrogen or oxygen on the work. These gases aid in prying off scale during pickling. Electrolytic pickling's advantages over chemical pickling can be stated as follows:

1. Pickling time is reduced.
2. The rate of pickling is affected to a lesser extent by changes in the acid concentration and by the iron salt accumulation in the solution.
3. Ferrous metals, including alloy steels, can be pickled much more readily than by a conventional acid pickle.

The acids used as an electrolytic pickle could be sulfuric acid, with or without fluoride additions, or proprietary acids (dry acid salts or liquid).

In cathodic pickling the work is made the cathode, and during pickling hydrogen is evolved on the work surface. Cathodic pickling would be selected when any of the following conditions are present:



1. Dimensionally accurate fabrication or machine parts.
2. Highly finished steel (#3 finish).
3. Fabrications having deep recesses.
4. Soils consisting of light oxides or smut.
5. Activating metals.

In any pickling operation there is always the problem of hydrogen embrittlement, and in cathodic pickling this danger is increased because of the evolution of hydrogen on the work surface. Usually the pickling time is rather short—30 sec to 1 min—thus the embrittlement factor is minimized.

Anodic Pickling

In anodic pickling oxygen is evolved on the metal surface. The oxygen formed on the work surface merely performs a scrubbing action in that it aids in loosening and removing the scale, rust, and smut. Consequently, all of the pickling action is accomplished by the acid solution. The advantage of anodic pickling over cathodic is that removal of heavy layers of scale and rust may be accomplished.

Anodic pickling does a better job in removing scales, rust, and embedded soils by attacking the base metal. In this type of pickling one must expect some metal loss and, in some cases, pitting of the surface. This loss of metal may be reduced or stopped with the use of 70% by volume sulfuric acid. The problem associated with using 70% by volume sulfuric acid is the danger of smut formation. This would be prevalent in high carbon steels.

MECHANISMS OF CLEANING

The removal of objectionable contaminants from metallic surfaces can be accomplished by mechanical processes, chemical processes, or a combination of both.

Mechanical Processes

1. The physical removal of surface layers by means of aggressive mechanical action.
    - Shot blasting with glass, aluminum oxide, sand, or dry ice (CO_2) pellets.
    - Mass finishing via vibratory mill or part-on-part burnishing.
    - Grinding.
    - Abrasive pad buffing.
2. The physical removal of surface contaminants with minimal base metal removal.
    - Gas scrubbing by electrocleaning, cathodically, anodically, or periodic reverse.
    - Impingement by high- or low-pressure spray.
    - Turbulence, such as that supplied by slosh washers or turbo washers, in which cleaning solution is turbulently flowed over the surfaces to be cleaned.
    - Cavitation supplied by ultrasonics.
    - Abrasive brushing in solution.
    - Abrasive slurry.

Chemical Processes

Solubilization is the cleaning method in which surface contaminants become soluble in the cleaning solution. Examples are the dissolution of iron oxide in acids or acrylic coatings in alkaline aqueous solutions.

Emulsification is the process by which a normally insoluble soil becomes uniformly dispersed in an incompatible solvent. The most common emulsion encountered by people is milk, in which insoluble fats and proteins are dispersed in water. Emulsification is accomplished by a combination of proper surfactants, cosolvents, and coupling agents.

Saponification is the reaction of oils containing reactive fatty acids with alkali to yield soluble soaps. An example of this mechanism would be the cleaning of a lard oil lubricant from stamped steel by the use of an aqueous cleaning solution containing significant amounts of sodium or potassium hydroxide.

Wetting is the method by which a soil is displaced from the substrate surface by the use of wetting agents that have a greater affinity for the substrate surface than for the soils present. The wetting agent can work by having the same action on the soil particles present. In both cases the attraction between soil and substrate surface is eliminated and soils are removed.

Complexing is accomplished by the use of chelators, sequesterants, or complexors. The soils—typically metal soaps or lubricants—form soluble complexes with those agents and are thereby removed from the substrate. Complexors also function to prevent redeposition of insoluble or suspended soils on the substrate surface, particularly in hard water locations. Examples of complexors are organic acids and their salts, polyphosphates, and zeolites.

Defloculation is the process by which soils are broken down into finely divided particles that become suspended in the cleaning solution. Defloculation is normally accomplished in combination with mechanical action.

Other Processes

The surface cleaning of metallic substrates can be accomplished by use of heat and high vacuum to volatilize soils and oxides.

TESTS FOR CLEANLINESS

The degree of cleaning required for the surface of a part is a function of, and dictated by, operations to follow cleaning. The cleanliness of a part can be described as a function of the removal of a specific surface contaminant such as oil and grease, oxides, or particulate matter.

Test methods used to determine the cleanliness of a surface range from crude to highly sophisticated. A summary of several tests follows.

Water Break Test

The water break test involves examination of a surface for the presence of a continuous water film that has "no water breaks." If a water-break-free film of water is present it is indicative of the absence of hydrophobic surface contaminants. Oils, greases, and water-insoluble organic compounds would be examples of hydrophobic contaminants. The water break test does not confirm the presence or absence of hydrophilic particulate contaminants or oxides.

White Glove Test

The white glove test is used to show the presence of particulate and, to a certain extent, organic contaminants on a surface after cleaning. The part may be tested while still wet from rinsing or after drying. The surface of the part to be tested is wiped with a white glove, cotton swab, or lens tissue. The material used to wipe the surface is then examined for the presence of black, gray, or off-white residue or oil staining. If contaminants are found to be present, microscopic examination or advanced chemical or surface analysis can be performed on the part surface or the item used to wipe the surface to determine the nature of the contaminants.

Other Methods

Sophisticated physical and chemical analytical methods can be applied to test for residual contaminants on surfaces that have been cleaned. Samples of parts that have been cleaned and dried can be immersed in a turbulent solution of a solvent. The solvent can then be analyzed for organic contaminants and insoluble particulate matter. The amount of contaminant found in the solvent is indicative of the degree of ceaning.

Surfaces of parts that have been cleaned can be subjected to special analysis to determine the presence of oxides, organics, and particulate contaminants. Specifications can be written for the allowable presence and concentrations of contaminants in critical cleaning operations.

Analytical techniques such as infrared microprofiling (developed by Sandia National Laboratories), X-ray photoelectron spectroscopy (Oak Ridge National Laboratory), and light reflective technology (Dow Chemical Inc.) have been used to analyze for residual contaminants in critical cleaning operations.

If soils are doped with compounds that exhibit fluorescence exposure of cleaned parts to ultraviolet light will confirm the presence or absence of residual soils.

Tests based on surface tension have been used to determine the cleanliness of surfaces. Care must be taken to ensure the use of test solutions specific to the substrate surface.

SAFETY

Unfortunately, one of the most overlooked aspects of industrial cleaning is safety.

The use of chemicals for industrial cleaning exposes the user to potential injury if proper safeguards are not employed. The potential problems are well documented in Material Safety Data Sheets, books, and articles that have been written over the years. The warnings are of little value unless they are read, understood, and acted upon by those handling, using, or working in areas in which the chemicals are used.

A summary of the safety aspects of chemical cleaning are as follows.

Acids

The use of acidic cleaners containing appreciable amounts of sulfuric acid can expose the worker to potential splashing due to exothermic reactions that can result in localized boiling. Additions should be made in a slow, controlled manner to prevent splashing and localized boiling. Acids should be added to water. Water should not be added to concentrated acids:

Addition of acid cleaner concentrates to replenish working solutions should always be made to cool solutions (<100°F). Without exception, acid-resistant goggles, face shield, boots, apron, and gloves should be worn by workers to minimize the potential for body contact with the acidic solutions.

Acid cleaners containing fluoride compounds can result in severe tissue damage. Precautions should be taken to avoid any contact with fluoride-containing solutions. If fluoride compounds are used, personnel should be trained in the treatment of fluoride burns.

The use of acid cleaning compounds can result in the evolution of flammable and explosive hydrogen gas. Care should be taken to avoid uncontrolled release of pressure when parts are cleaned in sealed cleaning chambers. Sources of spark or flame that can ignite accumulated hydrogen should be identified and removed from the area in which acid cleaning is conducted.

The use of acidic cleaners for cleaning sulfurized steel or parts that have sulfurized oil present can result in the generation of poisonous and flammable hydrogen sulfide gas. The same precautions employed for dealing with hydrogen evolution should also be employed for the potential evolution of hydrogen sulfide.

Acid cleaner tanks and equipment should be properly vented to keep worker exposure to mists and vapors below OSHA limits. The reactivity of substrate material should be evaluated prior to acid cleaning to prevent violent reaction due to incompatibility and/or part damage.

Alkaline Cleaners

The use of alkaline cleaners containing strong alkaline compounds, such as sodium hydroxide and potassium hydroxide, can result in strong exothermic reactions when working solutions are made or replenished. Additions should be made to water or working solutions in a cautious, controlled fashion to prevent splashing and localized boiling. Additions should only be made to cool solutions (<100°F). Water should not be added to alkaline powders.

The use of alkaline cleaners for etching or cleaning reactive metals, such as aluminum, zinc, or magnesium, will result in the evolution of flammable hydrogen gas that can accumulate in foam blankets or in enclosed cleaning equipment. Equipment should be ventilated and ignition sources should be removed from areas in which reactive metals are cleaned.

The use of alkaline electrocleaners will result in the evolution of hydrogen and oxygen. Tanks should be well vented to remove these gases. Foam blankets on electrocleaners should be sufficient to prevent misting without excessive accumulation of hydrogen and oxygen. Disconnect current prior to removing work from electrocleaning tanks to prevent hydrogen explosions. Personnel using, handling, or working in areas where exposure to alkaline cleaners is possible must wear alkaline-resistant personal protection consisting of safety goggles, face shield, gloves, apron, and boots. Respiratory protection should be worn when dust or mist is a problem.

Neutral Cleaners

Although the destructive effect of neutral cleaners on body tissues may be minimal, in many cases these cleaners are used hot and the possibility of thermal burns from splashing may exist. Additions to working solutions should be made slowly and cautiously in a controlled manner to prevent splashing. Additions should only be made to cool solutions (<100°F).

Equipment

A preventive maintenance schedule should be implemented for the inspection and repair of defective cleaning equipment. Hoist systems, exhaust systems, heating systems, and tank systems should be inspected on a routine basis for proper function and equipment integrity. Worn, corroded, or damaged equipment should be repaired or replaced upon discovery.

General

1. Never work alone when working with chemicals.
2. Read and understand Material Safety Data Sheets, technical bulletins, and drum labels for the materials you handle and work with.
3. Always wear the personal protective equipment specified in the Material Safety Data Sheets, technical bulletins, or drum labels.
4. If you are injured notify the appropriate personnel and get medical attention as soon as possible.
5. If a spill occurs notify the individuals in your facility who are properly trained to respond to chemical spills.

ELECTROCLEANING

by Nabil Zaki

MacDermid Inc., Kearny, N.J.

Electrocleaning is a cleaning process used in metal surface preparation, usually in preplate cycles. It is essentially characterized by the use of DC current and a specially formulated electrolyte. The work being processed may be used as anodes or cathodes, or both, depending on the application. Although electrocleaning is a different and distinct method of surface cleaning, it should be considered in the context of the complete surface preparation or preplate cycle. Such a general cycle might include: (1) soak clean, (2) rinse, (3) electroclean, (4) rinse, (5) acid activate, (6) rinse, (7) repeat steps 3 to 6 (optional), and (8) plate.

Electrocleaners as described here are alkaline and will generally follow alkaline soak cleaners and precede acid activation in the preplate cycle. The basic function of electrocleaners is to remove soils from the surface that could not be removed by simple immersion soak or degreasing steps. Examples of such soils are as follows:

Adherent residues not removed in the preceding soak cleaner. Such residues include oil, fingerprints, drawing compounds, and soils driven into surface porosity or applied under pressure. These soils are not generally removed by conventional emulsification, wetting, and displacement soak cleaners.

Finely divided particles, such as polishing compound abrasives, metallic fines from grinding or metalworking operations, carbon, and other alloying elements, may also be found on the surface. Often this fine particulate matter, generally referred to as smut, may be held to the surface by simple mechanical forces, electrostatically, or in a thin oil or grease matrix.

Metal oxidation products, the result of exposure to the atmosphere, or a thermal process such as heat treatment, forging, welding, etc.

As explained earlier, electrocleaning must be viewed as part of the overall surface preparation process. Although an electrocleaner step may not totally remove a particular type of soil, it conditions or modifies that soil for easier removal in the subsequent steps in the cycle. For instance an adherent oil residue may be loosened enough to be lifted in the following rinse tank. Surface oxides may be reduced or oxidized to a more soluble form to be easily dissolved in the acid tank.

ELECTROLYSIS OF ELECTROCLEANERS

As current is applied to an electrocleaner, the following electrochemical reactions take place, essentially electrolyzing water. The alkalies serve as the conductive medium.

At the anode:

$$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$$

At the cathode:

$$4H_2O + 4e^- \rightarrow 4OH^- + 2H_2$$

As can be seen, twice as much hydrogen is liberated at the cathode than is oxygen at the anode.

TYPES OF ELECTROCLEANERS

Electrocleaners are classified on the basis of two main interrelated criteria: (1) polarity of the work in the tank; (2) type of substrate being treated.

There are three types of electrocleaning modes as defined by polarity of the work in process and the applicability of each to a given substrate.

Anodic Electrocleaning

The work is connected to the anode side of the rectifier and is positively charged. The process is also known as reverse electrocleaning, since the polarity is opposite that of plating. As described under electrolysis, oxygen is liberated at the surface of the work (the anode) when current is applied. As the gas rises to the top, it creates a mechanical scrubbing action that loosens and lifts the soils.

Two other phenomena also take place. As oxygen bubbles are formed on the surface, they coalesce and grow before they rise in continuous layers. It is believed that the static charge holding fine particles to the surface is released through the layer of bubbles, facilitating their removal through the scrubbing action.

Chemical effects, oxidation, and drop in pH also take place at the anode surface. If excessive, the effect of oxidation can be seen, for instance, on brass, zinc, and silver as they discolor, stain, or etch. Special inhibited anodic electrocleaners are available for brass and zinc.

When nickel is anodically electrocleaned it will quickly passivate and prevent further plating unless reactivated. A similar effect is experienced with stainless steels. Regular steels are not adversely affected by the process, whereas high carbon steels are more sensitive and require moderation in electrocleaning. Alloys of lead, nickel-silver, and silver plate are attacked or tarnished by anodic electrocleaning.

As oxygen is liberated at the anode, the net pH value tends to decrease at the interface. This effect can be noticed on steel if an electrocleaner's alkalinity is too low by design or for lack of bath maintenance. The steel is more rapidly oxidized, and precipitated iron hydroxide forms on the surface. Parts exiting the tank will have a rusty or etched appearance, especially in high current density areas. The situation can be readily rectified by increasing the alkalinity of the bath or by reducing the current density below normal operating levels.

Cathodic Electrocleaning

The work is connected to the cathode side of the rectifier and is negatively charged. This is also known as direct electrocleaning. In this case, hydrogen is liberated at the cathode. As seen from the net amount of electrolysis, twice as much hydrogen than oxygen is generated at the cathode. Consequently, more scrubbing action and cleaning ability are expected. The use of cathodic electrocleaning, however, has not found a widespread use in the industry as the main electrocleaning mode for two reasons: (1) the concern with hydrogen embrittlement as a result of copious hydrogen release at the surface, and (2) the risk of plate out of charged impurities from the solutions on the cathodic surface. The latter may not be noticeable to the casual observer as the parts exit the tank, but leads to poor adhesion on plating. Contaminants leading to such adhesion failures are metallic fines, certain types of surfactants, colloids, metallic soaps, and hexavalent chromium dragged into the cleaner.

Cathodic cleaners, when kept clean and well maintained, are used for processing buffed brass, zinc, and white metal without tarnishing, and for electrocleaning nickel and high nickel steels without risking passivation. When used on steel and copper, to take advantage of their superior scrub-clean action, a secondary anodic electrocleaner should follow even for a few seconds. This step will deplate any impurities that may have plated on the work by cathodic action.

Periodic Reverse Electrocleaning

This method of electrocleaning of ferrous metals uses a combination of both anodic and cathodic cleaning modes. A periodic reverse (PR) unit is installed on the rectifier's output.

Table I. Recommended Electrocleaning Current Densities—Rack Applications[a]

	A/dm²	*Polarity*
Steel, low carbon	5–10	A, C
Steel, high strength	3–5	A
Stainless steel	5–8	C
Copper	5–8	A, C
Brass	2–4	A, C (anodic inhibited)
Zinc diecast	2–4	A, C (anodic inhibited)
Nickel and alloys	2–3	C
Lead and alloys	5–8	C
Silver and alloys	2–3	C

[a] In barrel applications, a fraction of the above current density values should be expected.

The PR unit has a switching mechanism that reverses the polarity at controlled and timed intervals. The work in the tank assumes alternating anodic and cathodic polarities for the specified cleaning time.

Typical settings include 10 sec cathodic then 10 sec anodic, etc. By changing the setting, more cathodic or anodic may be used to effect maximum cleaning. The unit can be programmed so that the last leg of the cycle is anodic before the timer shuts off the rectifier. This ensures removal of any charged particles that may have plated on the work during cathodic cleaning.

The continuous oxidation and reduction at the surface converts the oxides and scales on parts to more soluble forms that are picked up by cyanide or chelating agents built into the cleaner formulation. PR cleaners eventually become saturated with dissolved iron oxides and must be replaced. Where practical, they can be regenerated by plating out the iron cathodically. PR cleaning is very efficient in descaling and derusting high strength and spring steels without the use of acids in the cycle, thereby eliminating or minimizing hydrogen embrittlement.

OPERATING PARAMETERS AND PROCESS CONSIDERATIONS

Electrolysis is the main driving process in electrocleaners. The amount of gassing responsible for the scrubbing action at the electrodes is a function of the amount of current passing through the cell. Therefore, parameters controlling current should be considered.

Solution Conductivity. This in turn is a function of cleaner concentration and temperature at a given voltage. The higher the concentration and temperature (up to a practical level), the higher the conductivity and the amount of gassing.

Voltage Applied. Current increases with voltage, although the latter is kept to maximum values of 10 to 12 V. Higher values are known to cause "burning" or roughness on parts.

Surface Area Being Cleaned. This parameter controls current density and, for a given rectifier setting, will directly affect the cleaning efficiency.

Adequate recommended current density ranges for different basis metals are summarized in Table I. Values below these produce light to marginal electrocleaning. Higher values generally lead to etching and roughness of the surface.

Anode to cathode area ratios of 1:1 are adequate for most applications. The ratio is not critical as long as the specified current density values are maintained.

PROCESS CONSIDERATIONS

There are general considerations in the selection and proper use of electrocleaners.

Table II. Typical Operating Conditions for Electrocleaning

	Steel and Copper	*Brass*	*Zinc*	*Nickel and Chromium Alloys*
Alkalinity (as NaOH), g/L	50–100	15–20	15–20	30–60
Temperature, °C	60–90	50–70	50–70	50–80
Time, min.	1–5	1–3	1–3	1–5

Electrocleaner Formulation

Several proprietary formulations are available covering a wide range of applications. These formulations should provide the following properties.

A suitable degree of alkalinity for the metal processed, e.g., high alkalinity for steel, lower for zinc and brass.

A proper ratio of hydroxide to silicate to prevent insoluble silicate films from adhering to the work and affecting plate adhesion. Silicates are often used to prevent burning of steel at high current density. Nonsilicated cleaners, using different types of inhibitors, are also available. Water softeners and conditioners should be considered in hard water areas.

An adequate amount of wetting agent and emulsifiers. Although high levels serve as cleaning agent for excess oil and grease, they inhibit the gassing action at the electrode surface and reduce desmutting characteristics. Efficient desmutting electrocleaners will have just enough surfactants to reduce solution surface tension and promote a thin foam blanket to hold down gas misting during electrolysis. Bulk oil removal should be a reserved function of the preceding soak cleaner.

Typical operating conditions of electrocleaners are given in Table II. Suppliers of proprietary electrocleaners usually tailor the parameters to specific applications, which may vary from the values shown in Table II. Alkalinity figures expressed as NaOH may represent 20 to 80% of the total product formulation.

Process Control

Control of electrocleaners is usually done by titration of the alkali contents. Maintenance additions will replenish alkalies, as well as surfactants and other components included in the formulation.

Although the essential components can be maintained, contaminants build up and eventually interfere with the proper performance of the bath. Oils and grease, if not adequately removed in the preceding soak cleaner, may result in water breaks out of the electrocleaner tank. Grease etch is also a result of such a buildup. It shows as jagged etch spots after plating. It is due to uneven current distribution around nonwetted spots on the surface being electrocleaned. Hexavalent chromium trapped in cracked rack coatings and dragged into the electrocleaner is another source of contamination. This leads to drastically reduced cleaning and haze under nickel plate.

Stripping chromium plated parts for rework in the process electrocleaner has a similar effect. Hexavalent chromium contamination can be readily detected as the cleaner turns yellow-orange and foaming seems to subside. Compatible chromium reducers are used to counter this effect. They reduce the chromium to trivalent if the cleaner is not heavily chelated and allow most of it to precipitate as the hydroxide. The solution color changes to light green, indicating the reduction process has taken place.

Equipment Maintenance and Operation

Corrugated or mesh steel can be used as anodes or cathodes to provide optimum surface area and solution circulation. Periodic cleaning of the anode/cathode is necessary to remove

Table III. Common Electrocleaning Problems

Problems	*Probable Causes*
Etching, tarnishing	Too high a current density Cleaner noninhibited for nonferrous metals Wrong polarity Temperature too high for nonferrous metals Excessive oil in solution
Roughness	Cleaner too weak causing "burns" on steel Excessive current density in anodic cleaning, pulling alloying elements to the surface. In cathodic cleaning, depositing charged particles and smut on surface Incomplete rinsing of electrocleaner
Haze under plate	Cleaner temperature too high causing dry-on film Cleaner too weak Incomplete rinsing after cleaner Inefficient soak or precleaning prior to electrocleaning Hexavalent chromium contamination
Poor adhesion, blisters, pitting of plate	Cleaner too weak Current density too low or too high Cleaning time too low or too high Reverse of intended polarity Hexavalent chromium contamination Insufficient rinsing after cleaning Excessive oil/grease in cleaner

plated-on smut, oxides, and other charged particles. Using the tank as the anode or cathode is not recommended, as it leads to uneven current distribution and a source for stray current. Many electrocleaning problems, such as under- and over-cleaning, have been traced back to such a practice. A summary of common problems is given in Table III.

Polypropylene or lined tanks are recommended for alkaline electrocleaners fitted with steel, stainless steel, or Teflon heaters. Recirculating pumps are recommended to prevent stratification and ensure overall homogeneity. It should be noted that solution inlet and outlet must be located at two opposite diagonal top and bottom corners of the tank for efficient solution movement.

Cleaner filtration is gaining in popularity with the aim of prolonging the bath life between dumps. Several filtration techniques have been proposed, ranging from simple bag filtration to complete systems of oil skimmers, coalescers, and ultrafiltration. Since the cost of such systems varies appreciably, a feasibility study must be undertaken before adopting a particular system. In general, however, it has been reported that any type of filtration does increase the bath life at least by 20% and up to five times or more.

LIQUID CLEANERS

The use of liquid cleaners to replace powders has been gaining momentum and wide acceptance in the industry. These new cleaners are formulated to economically provide all the performance criteria of the powders. The advantages of liquid cleaners include the capability of automatic feeding tied to conductivity controllers. The automated system continually monitors the solution strength and makes additions on demand. Consequently, better bath control is achieved, eliminating wide swings in concentrations. Automatic recording capabilities of concentration and temperature can be achieved for statistical process control.

Tank additions of liquid concentrate eliminate the hazards associated with additions of alkaline powders to hot cleaner solutions. As a result of better controls, these liquid systems have substantially increased bath life in many installations.

Another advantage confirmed by users of liquid cleaners is sludge reduction on waste treatment by 70 to 80%, which adds to the economical advantage of these systems.

ELECTROCLEANING OF STRIP AND WIRE COILS

Strip and wire are continuously fed through the line. There is no direct contact with anodes or cathodes in the electrocleaner tank. A bipolar electrical effect is used to provide the polarity as follows. Two separate steel grids are positioned several feet apart in the direction of work flow. The first grid is anodically connected, the second, cathodically. The strip travels between two closely spaced jaws of each grid without touching them. As a result of the bipolar effect, the strip assumes the opposite charge of the grid. It becomes cathodic through the first grid, then anodic through the second, achieving the desired electrocleaning effect.

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THE ART AND SCIENCE OF WATER RINSING

by Ted Mooney

Finishing Technology, Brick, N.J.

Rinsing is the removal of a harmful clinging film of process solution from a workpiece by substituting in its place an innocuous film of water. Efficient rinsing comprises achieving the desired end while expending as little work or effort as possible.

The principles and formulas underlying the science of rinsing were developed and widely published decades ago by Joseph B. Kushner, J.B. Mohler, and others. Not expecting the findings from this earlier work to change, why rehash the subject? The answer to this rhetorical question lies in the meaning of the word "effort." It doesn't mean merely an expenditure of brawn, it also implies allocating a portion of a limited resource.

Metal finishers must continuously reexamine what "effort" means. A few decades ago, its meaning might have been approximately equivalent to "hours of labor." But the cost of chemicals has become an increasingly important component of "effort." And as water shortages hit many areas of the U.S. and the world, the amount of water required to operate a process has become a critical part of the definition of "effort."

An old joke tells of a bakery not being able to bake any more doughnuts because it had run out of holes. Finishers today don't find the line amusing: the cost of solid-waste disposal imposes strict limits, and the resource that demands the most careful husbanding may be the amount of emptiness left in the dumpster. Similarly, with tight wastewater effluent standards, each milligram of metal we allow down the sewer today may equate to one less milligram of entitlement we hold in reserve for tomorrow. The constant pressure to improve quality permits fewer and fewer defects; and continuing the doughnut-hole analogy, permissible-number-of-rejects is becoming a strictly rationed resource against which we must hoard our ration tickets jealously.

For these reasons, although the rinsing formulas themselves may be abiding, the shifting sands of changing times demand that we constantly reevaluate the subject with the day's priorities in mind.

WHY RINSING IS NECESSARY

In general, it is necessary to thoroughly rinse the work between the various treatment stages. For example, ware carrying off an unrinsed film of alkaline cleaning solution would quickly contaminate a subsequent acid pickle, which, if in its turn went unrinsed, would rapidly contaminate the plating bath. Subjecting the work to a high level of contamination in the rinse tanks can also cause passivation of the work surface or encourage precipitation of reaction products on the work. If the final processing solution is not properly rinsed, salt spotting will occur, which may cause etching or be otherwise harmful, and in any case will be unattractive. Thus, it is necessary to dilute the clinging film of process solution to such an extent that problems such as salt staining and contamination of subsequent processes are limited to manageable levels.

The literature gives advice concerning what dilution ratio is usually required in rinse tanks. A very general rule of thumb is that a dilution ratio of 1,000:1 is a good starting point in many cases. Then trial and error or a more rigorous statistical process control approach can be employed to get a more exacting answer.

EQUILIBRIUM RINSING

The best approach to understanding a complex phenomena usually is to begin with the obvious and build upon it. So, picture an empty mixing vat. Then envision adding to this vat

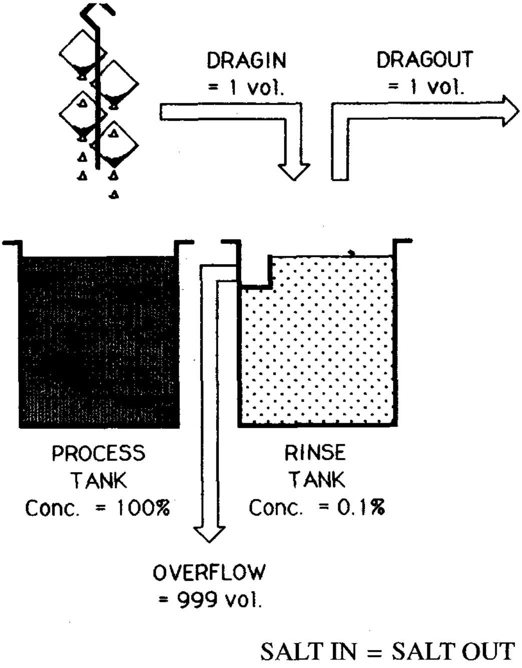


Fig. 1. Single-stage rinse.

1 part of concentrated plating solution and 999 parts of water, and thoroughly stirring the mixture. The mixture will be 1 part plating solution per 1,000 total parts, or a 0.1% concentration.

The next step in extending our understanding of rinsing is to comprehend what is known as an equilibrium process. Start with the same 1,000 parts of 0.1% mixture but, instead of leaving well enough alone, continue to add plating solution and water, in the ratio of 1:999, until the mixing vat overflows. Without going into elaborate proofs, recognize that things are in balance here. The vat contained a 0.1% solution and what is being added is a 0.1% solution, so what is overflowing must be a 0.1% solution also.

Now, imagine that we had started this process of continuously overflowing the vat years ago, and that it has continued uninterrupted ever since. We are confident that the overflowing rinsewater is and always has been of 0.1% concentration. Then someone tells us that they hate to break this bad news ... but years ago when the experiment was started they had forgotten to add the 1 part plating solution; effectively, we had started with 1,000 parts water instead. Our intuition tells us that the concentration in the overflow today can't possibly be dramatically influenced by the starting conditions all those years ago, and our intuition is right: the system long ago reached a condition so close to equilibrium that the difference is unmeasurable.

This is what we mean when we say a process approaches an equilibrium condition; it really doesn't matter whether the vat originally contained the desired 1:999 mixture, or was pure water, or was straight plating solution. If we have added liquid in the ratio of 1 part plating solution to 999 parts water for a substantial enough period of time, then for all practical purposes the concentration in the vat is 1 part to 999, regardless of the initial conditions. This is the real-world situation in the majority of rinsing applications.

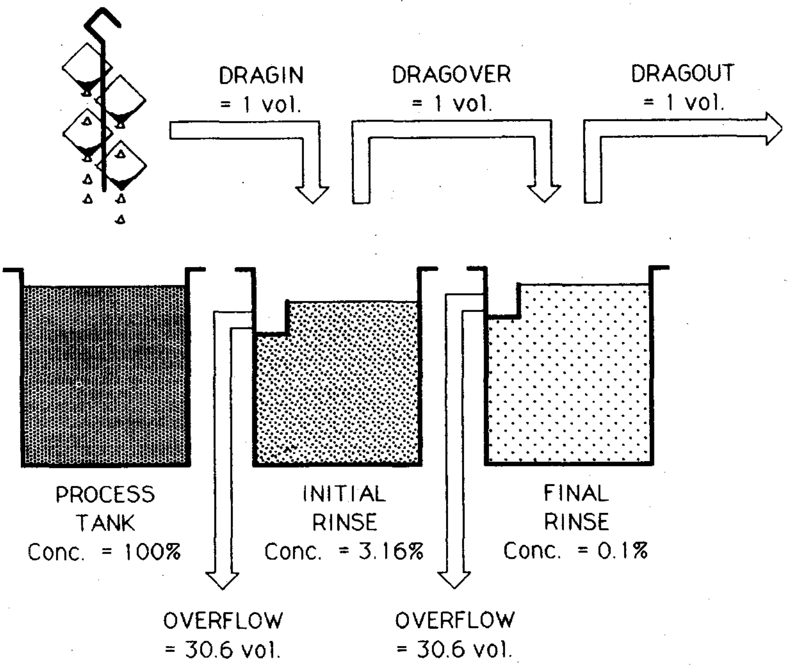


Fig. 2. Double-stage rinse.

SALT IN EQUALS SALT OUT

Mohler succinctly described the equilibrium condition for a rinse tank with one simple equation whose logic is irrefutable:

SALT IN = SALT OUT

The chief mechanism which brings SALT IN to a rinse tank is the clinging film of solution, which adheres to the workpiece when it is removed from the process tank. This is usually called the drag-in. The main mechanism that carries SALT OUT of the rinse tank is the overflowing rinse water. Some salt is removed from the rinse tank by drag-out too, but this is a minor factor. Figure 1 illustrates a rinse tank in equilibrium.

If we assume perfect mixing (about which we'll have more to say later), we can calculate what overflow rate is needed in order to hold the concentration in the rinse tank down to a desired value. For example, if we know the drag-in to be 1 volume of plating salt per hour, and we have found that the acceptable concentration in the rinse tank is 0.1%, we can calculate the required overflow rate as follows:

SALT IN = 1 vol. of drag-in × 100% conc. = 1 unit of salt
SALT OUT = SALT IN = 1 unit of salt
= vol. out × 0.1% allowable conc.
Vol. out = 1 unit of salt out/0.1% conc. = 1,000 vol.
Required overflow rate = 1,000 vol. − drag-out vol. = 999 vol.

Figure 2 shows the same problem being addressed, but with two rinse tanks employed.

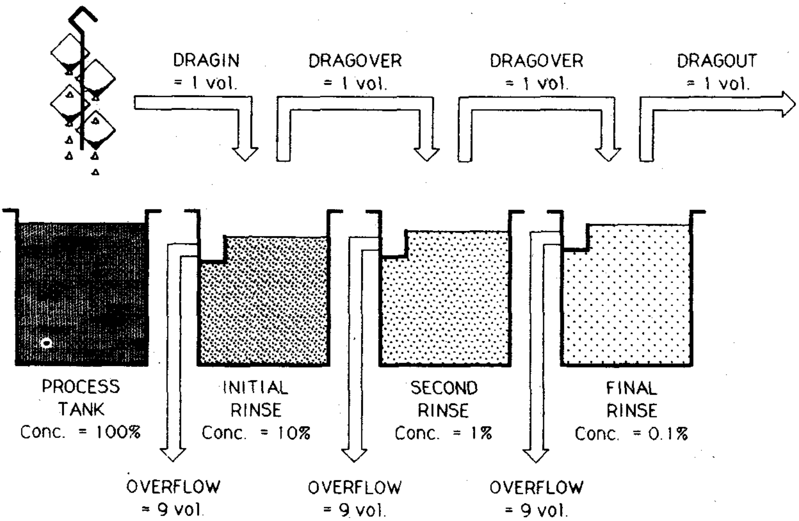


Fig. 3. Triple-stage rinse.

The overflow rate need only be 30.6 volumes per tank, or 61.2 volumes total, to achieve the same 0.1% concentration in the final rinse. The total rinsewater leaving each tank is 31.6 volumes (30.6 via overflow plus 1 via drag-out). Note that 31.6 is, not coincidentally, the square root of 1,000. If the concentration of the process tank is 31.6 times the concentration in the initial rinse, and the concentration in the initial rinse is 31.6 times the concentration in the final rinse, the concentration of the final rinse is 1/1,000 the concentration of the process tank.

If the goal is to reduce the concentration in the final rinse to the required value, with the lowest expenditure of rinse water, the optimum way to allocate the water is to distribute it evenly between the two rinses. But remember our opening assertions, this may not in fact be the main goal.

When a third rinse is added, as shown in Fig. 3, the required overflow rate is reduced to about 9 volumes per tank (the total amount of rinsewater leaving the tank is 10 volumes, the cube root of 1,000). If a fourth rinse is used, the required flow rate is about 4.6 volumes per tank. Thus, multiple rinses are gainfully employed where high dilution ratios are required, as for example in the last rinse before drying. Where minimal rinsing is required, for example between a soak clean and electroclean process, it may prove difficult to justify even two rinses.

COUNTERFLOW RINSING

Figure 4 illustrates the use of a technique called "counterflow rinsing," whereby the water overflowing from the final rinse is used as the input source for the initial rinse. Because the same rinsewater is used twice, this method cuts the required water flow almost in half (compared with Fig. 2), to about 31.1 volumes total.

Solving the formulas for counterflow rinsing is a little more complicated because the rinsewater flowing back from the final rinse to the initial rinse carries some salt with it.

Looking at the initial rinse:
SALT IN = 1 vol. of drag-in × 100% conc. + counterflow vol. × conc. of final rinse
SALT OUT = (1 vol. of drag-over + overflow vol.) × conc. of initial rinse

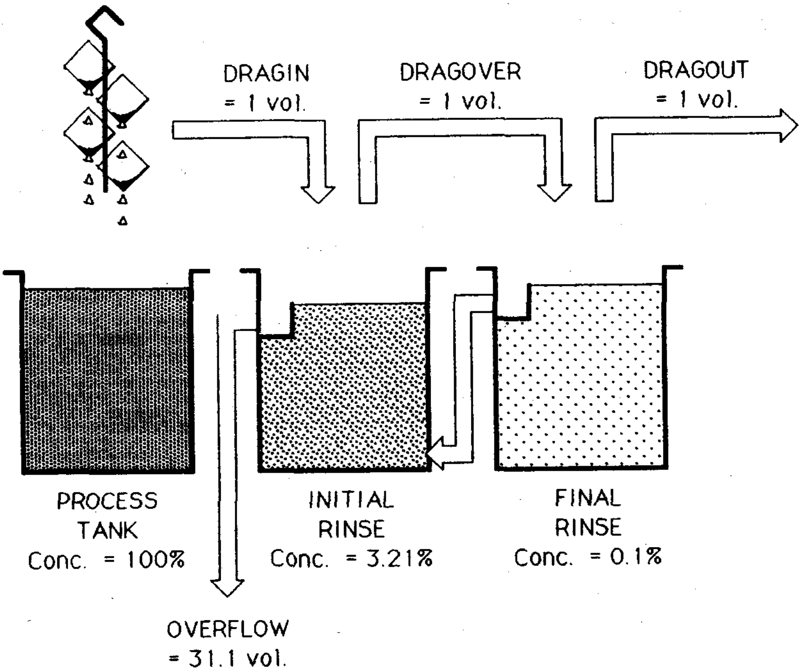


Fig. 4. Counterflow rinse.

Looking at the final rinse:

SALT IN = 1 vol. of drag-over × conc. of initial rinse
SALT OUT = (1 vol. of drag-out + counterflow vol.) × conc. of final rinse

The concentration in each rinse thus depends on the concentration in the other rinse. The traditional way of finding the concentrations involves using special mathematical techniques designed for the solution of simultaneous equations; but today, with the ready availability of personal computers, recursion (a fancy name for trial and error) will quickly yield the answer directly from the above equations without complicated mathematical manipulations.

Note that our analysis is for a theoretical counterflow arrangement. Real-world experience indicates that many counterflow rinse tanks do not operate properly in that the placing of a load of work into the initial rinse impels a backwash of relatively dirty water into the final rinse. Care must be exercised to ensure that the gravity head is sufficient, and that the piping is free of air locks and large enough to ensure that the actual rinse tanks function according to the theoretical model.

Where counterflow rinsing is desired, but the requisite gravity head absent, it is possible to convey the rinsewater from one tank to another with a simple device called an air lift, which creates an artificial gravity head through the principle that highly aerated water is significantly lighter than an equivalent volume of normal rinsewater.

Where space constraints or production realities preclude adding additional rinse tanks, it may be possible to install a bank of spray nozzles above the rinse tank to serve as a second rinse. To adhere to the counterflow principle of fresh water being used only in the final stage, the spray should be activated only while the work is exiting from the rinse tank.

IT'S ALL FOR NAUGHT

Because in an equilibrium situation, "SALT IN = SALT OUT," none of the illustrated rinse tank arrangements accomplishes anything toward changing the fact that all of the salt dragged out of the process tank eventually goes on to treatment. In all cases, the only thing varying is how much water is consumed, but minimizing waste and the amount of metal requiring treatment is usually an important goal, and is best achieved through actions directed at preventing the solution from being dragged out of the process tank in the first place.

Slow withdrawal of the workpieces from the process tank, and ample drainage time, are keys. Racking the parts to minimize pockets, and tilting the pieces to encourage drainage, will prove beneficial. Orienting the parts so that the low point is a corner, rather than an edge, slashes drag-out. Studies have shown that small flat plates dragged out only one sixth as much solution when racked diagonally.

Maintenance of plating racks is important so that bubbles in the coating do not exaggerate drag-out. Poorly maintained racks may drag out more solution than the work itself. In barrel plating, specifying a large perforation size will aid drainage. It is the nature of the plastics used in the construction of plating barrels, when subjected to the tumbling action of the work, to peen over and block the perforations. An investment in replacement barrels, or labor to redrill the holes, will probably prove beneficial.

RECOVERY SYSTEMS

All of the solution that has left the process tank is not necessarily lost. It may be possible to return a portion of the solution, or at least its metal value, to the process tank. One way to do this is with a drag-in/drag-out tank, which consists of a stagnant rinse tank that the work enters immediately before and immediately after the process tank. The concentration in this tank approaches an equilibrium value of 50%, such that each load processed returns half of its drag-out to the process tank.

There are many technologies for recovering process solutions or their metal values from the rinsewater, for example evaporation and electrowinning (see chapter elsewhere in this *Guidebook* on recovery technologies). In most cases, the greater the concentration in the recovery rinse, the greater the efficiency of the recovery process, so that maximizing the concentration in the recovery rinses may be a goal of the rinsing strategy.

This usually will suggest decoupling the recovery rinse from the other rinses, rather than employing the counterflow principle because, with the recovery rinse being of a high concentration, a very low flow rate is desirable to minimize the amount of chemical carried off in the overflow. The more dilute final rinses can have a fairly substantial flow without carrying much chemical out of the system.

To illustrate this fact, consider Fig. 5, which is the same as Fig. 2 except that evaporative losses in the process tank make it possible to return one-half of the volume of rinsewater from the recovery tank. Operated in this fashion, and comparing the results with Fig. 2, the benefit of the evaporation is shown to be negligible.

In Fig. 6, however, we reduce the flow rate in the recovery rinse so that the concentration can build up. Then the same small volume of rinsewater returned to the plating tank carries a significant amount of plating salt back with it; using the numbers in our example, the plating solution lost to drag-out is cut by 25%.

Note that this advantage was not gained without penalty: although we reduced wasted plating solution, we needed to drastically increase the rinsewater flow to hold the same 0.1% concentration in the final rinse. This illustrates two points: first, that some of the rinsing goals may be mutually exclusive; second, that it will usually require more than two tanks to effect an efficient recovery and rinsing operation.

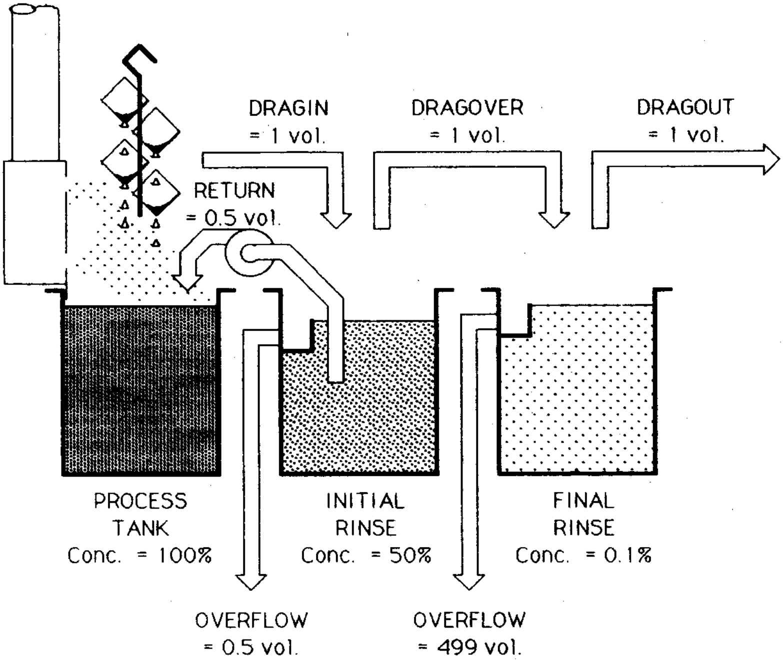


Fig. 5. Recovery from a high-flow rinse.

PERFECT MIXING

The rinsing equations discussed above assume perfect mixing, meaning that the surface film of process solution has completely diffused into the general rinsewater, forming a homogeneous solution. If insufficient rinse time is allowed, this may not always be the real-world situation; nor may it be possible and practical to leave the work in the rinse tank long enough for this diffusion reaction to reach completion.

Agitation methods that allow convection effects to hasten the diffusion will improve rinsing efficiency. Air agitation, cathode rocker agitation, or other mixing methods may help achieve this end (see chapter elsewhere in this *Guidebook* on solution agitation and mixing).

An easy method that is effective in improving rinsing efficiency is "double-dipping," simply immersing the work in the rinse, removing it, and reimmersing. This has been demonstrated to be effective with racked work, and would be expected to be even more beneficial in barrel plating.

RINSE TANK DESIGN

Care should go into the design of rinse tanks so that they may operate as efficiently as possible. The overflow weir must be level and full-length to minimize short-circuiting; lacking a level overflow weir, the fresh water added to the tank will take the path of least resistance, rather than mixing thoroughly with the contents of the tank. This would be a waste of water, as the overflowing wastewater would then be less concentrated than the tank contents.

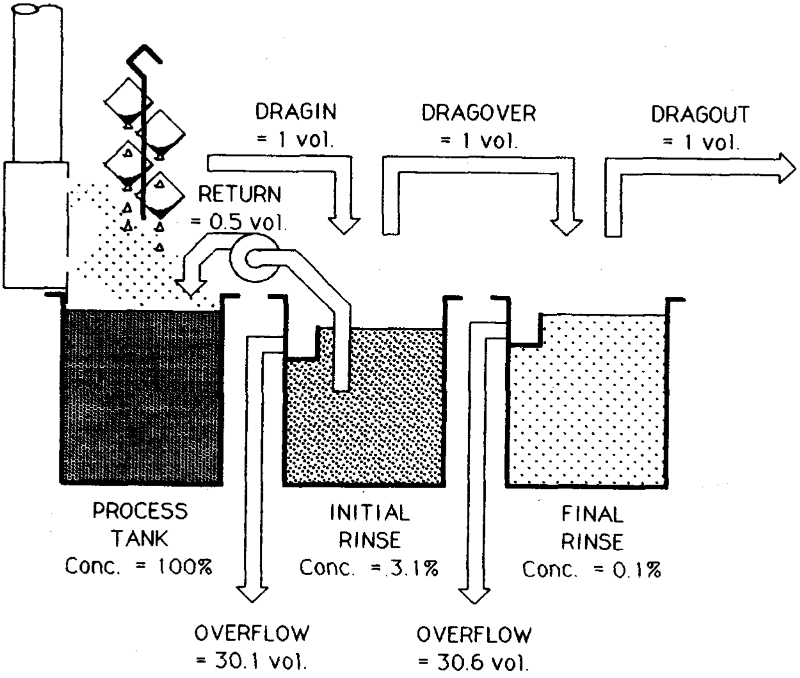


Fig. 6. Recovery rinsing.

Equally important to promote good mixing is that the fresh water inlet be brought to the bottom of the tank and distributed via a perforated sparge pipe.

As noted in the earlier discussion of counterflow rinsing, it is extremely important that sufficient gravity head exist, and the details of the design be properly executed, to preclude a backwash of dirty water from the initial rinse to the final rinse.

MINIMIZING WATER USAGE

Once the desired dilution ratio is known, equipment may be installed that will help hold the concentration of contaminants down to the desired level with minimum waste. For example, a timer and solenoid valve can be rigged to deliver a fixed quantity of water to the rinse tank with each load. The timer can be actuated by foot treadle, limit switch, or, in the case of automatic lines, from the machine's control system.

If loads vary in frequency and drag-out volume, a better remedy may be to employ a conductivity controller that is adjusted to feed additional rinse water only when contaminant concentration exceeds the acceptable level.

It is almost always worthwhile to incorporate flow restrictors, which are simple plumbing devices designed to govern the flow of fresh water to the rinse tanks, holding it to the desired setting despite fluctuations in water pressure.

Designing an efficient rinsing system requires an understanding of the principles, clear thinking regarding the specific goals, and careful attention to the details of the installation.

DEIONIZATION FOR ELECTROPLATING

by Stanley Hirsch

Leeam Consultants Ltd., New Rochelle, N.Y.

Water is an essential component of the electroplating process and is used in various steps from the beginning to the end. The purity of the water with respect to its mineral and organic content critically affects the quality of the plated part.

FUNDAMENTALS OF DEIONIZATION

The water used in so many metal-finishing processes is simply a solution of various inorganic salts. These dissolved impurities are cations (positively charged particles) and anions (negatively charged particles).

The process of deionization or demineralization as applied to the treatment of water involves the exchange of ions to remove any or all dissolved ionic impurities from the water. Because of the developments in the process of deionization water of the highest quality is readily available in ample quantity and at reasonable cost. Although there is careful quality control of the chemicals used in metal finishing little attention has been given to the effects of the impurities in the process water.

The ions most frequently found and their characteristics are outlined in Table I.

Two of the most common cations are calcium and magnesium, both of which are associated with the characteristic of water hardness. The ion-exchange process for removal of these cations is known as softening. The alkalinity of water derives from the bicarbonate, carbonate, and hydroxide ions. These are removed through an ion exchange process called dealkalization.

Silica and carbon dioxide exist as weakly dissociated ions in natural water and can also be removed by ion exchange. It is most important to remove silica (SiO_2) when the water is to be used in a hot bath. Silica, when heated, acts similarly to calcium and magnesium and forms a scale, which is very difficult to remove. Most nonionic organic compounds are not removed by ionic exchange.

Ion-exchange resins are insoluble electrolytes consisting of a high concentration of polar groups (acidic or basic) incorporated in a synthetic, resinous polymer vehicle. These resins are either cation exchangers or anion exchangers. Reactions of both types involve simple ionic equilibria. In the following typical reactions R^- represents the cationic polymeric resin, R^+ the anionic polymeric resin, M^+ the cation, and X^- the anion.

Table I. Dissolved Impurities in Water

Ions	*Impurity*	*Water Characteristic*	*Removal Process*[a]
Cations	Ca^{+2}	Hardness	Softening
	Mg+2	Hardness	Softening
	Na^+		
	K^+		
Anions	Cl^{-2}		
	SO_4^{-2}		
	HCO_3^{-1}	Alkalinity	Dealkalization
	CO_3^{-1}	Alkalinity	Dealkalization
Weakly dissociated ions	SiO_2		
	CO_2		

[a] The removal process for any or all ions is called demineralization.

Table II. Purity of Water Obtained from Various Production Methods

Water Production Method	*Purity*[a]
Water after 28 distillations in quartz	23,000,000
Water treated by mixed-bed resin system	18,000,000
Water after three distillations in glass	1,000,000
Water after a single distillation in glass	250,000–500,000
Water treated by a multibed resin system	250,000–1,000,000

[a] Specific resistance in W-cm.

$$R^-H^+ + M^+X^- \rightarrow R^-M^+ + H^+X^- \quad (1)$$

$$R^+OH^- + M^+X^- \rightarrow R^+X^- + M^+OH^- \quad (2)$$

Eq. (1) shows a strong-acid-type cationic resin exchanger and Eq. (2) shows a strong anionic resin exchanger.

These equations demonstrate the process of water demineralization. When water containing minerals contacts a cationic-exchange resin in the hydrogen form the effluent will be the acid of the anions present. The acid is then stripped of the anions by flowing through an anionic-exchange resin in the basic form. This is the basis of multiple-bed demineralization.

With this system water can be produced with a specific resistance of 250,000 to 1,000,000 W-cm. The total electrolyte content in water treated this way can be as low as 2 ppm. The small amount of solids still remaining after the two-bed treatment is attributed to the complete reversibility of the reaction. Some salt must inevitably leak through the bed.

To obtain water with greater purity, the acid form must be removed as quickly as it is generated, allowing the reaction to proceed to completion. Systems to accomplish this have been devised using alternating beds of cation and anion exchangers.

Subsequent systems have been developed where it is possible to mix the cation and anion resins in one column having an infinite number of cationic and anionic exchanges as the water flows through the single column mixed-bed dimineralizer. This will produce water with the highest purity obtainable, 0.10 ppm. The theoretical maximum quality of water that can be produced would have a specific resistance of 26,000,000 W-cm. Table II compares water purity based on its method of production.

APPLICATIONS OF DEIONIZED WATER FOR PLATING

The quality of the water used in plating is a factor affecting the plating results in terms of the following characteristics: adhesion, brightness, uniformity, smoothness, pitting, spotting, staining, and clarity of deposit. Water can be obtained from several sources, including raw surface water from rivers, lakes, etc.; raw groundwater from wells; and treated water from municipal reservoirs. The various components in these waters that can cause problems in plating operations will vary widely. Generally, the reservoir water is of a higher quality and is more consistent in its composition than is either raw surface or groundwater.

In the plating cycle there are four major stages in which water is used:

1. Rinsing of parts prior to plating
2. Makeup of plating solutions
3. Replenishment of plating solutions because of evaporation and drag-out losses
4. Final rinsing of the plated article before drying.

How important it is to use deionized water depends on both the source of the water and the particular step of the plating cycle.

Table III. Problems Caused by Use of Contaminated Water for Bath Makeup

Type of Bath	*Roughness*	*Pitting*	*Haziness*	*Reduced Throw*	*Brittleness*	*Deposit Stress*	*Lower Efficiency*	*Dullness*	*Darkness*	*Anode Polarization*	*Burning*
Cadmium cyanide	Ca							O			
Chromium			Fe	Na				Cl			
Copper (acid)			Cl		O,Fe					Cl	
Copper cyanide	Ca	O						O			
Copper pyrophosphate	Ca	O		O	O			O			
Lead fluoborate	SO_4								O		
Nickel (electroless)	O,Fe	O						O			
Nickel sulfamate		O	O,Fe			Na					
Nickel (Watts)		O	O,Fe			Na					
Silver cyanide	Ca,O		O								
Tin (acid)									Cl,Fe		
Tin-lead fluoborate	SO_4								O		
Zinc chloride	Fe						Fe				Fe
Zinc cyanide	Ca		O								

Key to common contaminants causing problems. Cations: Ca, calcium; Fe, iron; and Na, sodium. Anions: Cl, chloride; and SO_4, sulfate. Organics: O.

It is necessary to use the highest quality deionized water for replenishment of solutions where evaporation and drag-out have occurred. When plating at temperatures above room temperature the plating baths are evaporators and therefore concentrators. If the water used to replace water lost through evaporation contains dissolved solids the solids will not be evaporated but, rather, will concentrate in the bath and thus cause plating problems.

Ranking next in importance is the water used to make up the plating solutions. The various components existing in the water often contribute to problems in the plating operation. Table III summarizes these problems as related to the use of water for replacement of evaporation and drag-out losses and for makeup of the different plating baths.

Somewhat less critical, but also a factor that must be considered, is the quality of the water used in the rinsing of the plated article before drying. Demineralized final rinsewaters eliminate the possibility of water spots and stains with their resulting problems. It is almost a necessity to use demineralized water in the final rinse before applying any organic coatings if good adhesion is to be achieved.

The quality of rinsewater after alkaline cleaning or pickling prior to plating is of lesser importance than in the aforementioned steps. The ions present in the water, which are dragged into the plating tanks and concentrate there, are minimal.

PROBLEMS WITH DEIONIZED WATER

The use of deionized water as discussed above is by no means a panacea for preventing problems in plating. Although dissolved minerals have been removed during deionization the water can contain a variety of organic contaminants. Some of these may be dissolved organic compounds and microorganisms such as yeasts, molds, and bacteria. These impurities can cause a variety of problems that must be dealt with. Table III lists the problems due to the organic contamination that can occur in the various plating baths.

The amount of organic contamination will vary according to the water source. Reservoir water, which has been treated to remove organisms so that it is potable according to the U.S. Public Health Standards, may not meet the more stringent specifications for water quality required for many metal-finishing procedures. Water that is safe for drinking may be unsuitable for electroplating. Well water contains few organic contaminants because many have been filtered out as the water passes through sand and rocks.

Raw surface water potentially contains the greatest amount of organic contamination. This contamination is influenced by the weather and increases substantially during heavy rain storms when the water sources are stirred up.

In addition to the original organic contaminants remaining in the deionized water further contamination can occur during the production and storage of deionized water. Traces of organic matter are leached from ion-exchange resins during periods of idleness. The first effluent following such an idle period should be discarded before using the water.

Heavy organic contamination can occur in the storage tank used for deionized water. When the water is stored at room temperature or above the growth of algae is encouraged. When this occurs tanks must be washed thoroughly with a sodium hypochlorite bleach solution to destroy the algae.

TREATMENT FOR REMOVAL OF ORGANIC CONTAMINATION

Before water is used for any rinsing or electroplating processes it is necessary to remove organic contaminants from the deionized water by carbon treatment with an activated charcoal filter. The water used for replenishment of losses in the plating baths due to evaporation and drag-out must be of the highest purity to avoid concentration of the organic contaminants.

Because large quantities of deionized water are normally used during the rinse cycles of the plating operation it is usually kept in storage tanks. It is best to carbon treat the water before putting it into the tanks to prevent the growth of algae there. If algae grows in the storage tanks, and this water is used, problems with adhesion will result.

To check whether the organic contamination level is high enough to cause problems in electroplating a simple procedure is suggested. Concentrate five liters of the water being used for replenishment down to 100 cc by evaporating it on a hot plate. Prepare two Hull cells, one using this 100-cc sample and another using the original water before evaporation. If the two panels are the same, and of good quality, the water should present no problems and may be used without carbon treating. If, however, the panel from the water that has been concentrated 50 times shows organic contamination it is important to carbon treat the water prior to using it for replenishment purposes. Please note that all chemicals, addition agents, and brighteners used must be identical in both Hull cells to apply this test.

ENCLOSED VAPOR DEGREASING SYSTEMS

by Joseph Scapelliti

Detrex Corp., Bowling Green, Ky.

Historically, vapor degreasing has been the cleaning process of choice for the majority of manufacturers. It is primarily used for batch cleaning of parts in such industries as general metalworking, automotive components, aerospace, and electronics. Vapor degreasing traditionally used CFC-113 and 1,1,1–trichloroethane solvents. Recent developments have forced both manufacturers and chemical companies producing solvent to reexamine current cleaning processes.

It was the discovery that these solvents, commonly used in the cleaning process, were responsible for the depletion of the ozone layer that eventually lead to the Montreal Protocol. The Protocol called for a phased withdrawal of these solvents from the world marketplace. In the United States, taxes have been levied on continued use of these solvents and the U.S. EPA now requires warning labels on products that were manufactured using these solvents and placed into commerce. As a result, some solvent manufacturers have announced that they will cease production of these materials. These events have created many problems for manufacturers who rely on the vapor degreasing process.

The "magic bullet" (a drop-in replacement solvent) that provides high threshold limit values (TLVs) and the good cleaning characteristics of 1,1,1–trichloroethane and CFC-113 without any ozone-depletion potential does not exist at present. Chemical manufacturers report that if replacements are developed, they will be more costly and perhaps have lower boiling points and lower TLVs. Most chemical companies won't even speculate on when these replacement chemistries might be available.

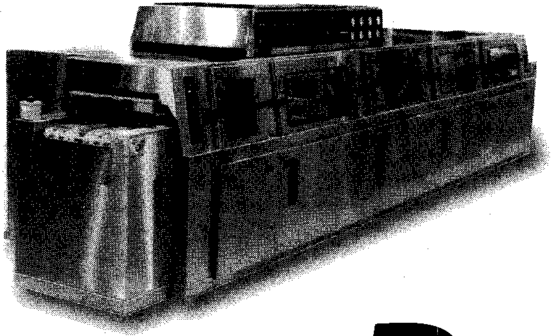
The consensus is, however, that new replacements will not be available before the existing chemistries are phased out. This has mandated industry to seek alternatives to the conventional vapor degreasing process and it must choose from technologies and chemistries that are currently available.

CONVENTIONAL VAPOR DEGREASING

Traditionally, a vapor degreasing system has been a open-top tank with a heater unit at the bottom to boil the solvent and a cool surface at the top of the unit to condense the vapors (Fig. 1). Operation of these units is quite simple, but effective. Vapors from the boiling solvents condense on a cool part, which flushes off the oil, grease, and soil. When the temperature of the part reaches the temperature of the vapor, condensation ceases and clean, dry parts are then removed from the tank. This occurs because solvent vapors rise, displacing air in the tank. Vapors are confined by condensing coils and a water jacket below the freeboard area in the upper part of the tank. As the solvent vapors reach the cool zone, they condense on the cooling coils. This process, while relatively efficient and cost effective, permits an extremely high percentage of the solvents to escape into the atmosphere. Chemical companies continue to research alternative solvents, but even the most optimistic forecasts indicate that regulatory deadlines will arrive before new chemical alternatives are available.

BENEFITS OF ENCLOSED VAPOR DEGREASING

The benefits of vapor degreasing are well known. In a vapor degreaser, cleaning, rinsing, and drying all take place using one chemistry and, when compared with other cleaning processes, vapor degreasing uses less energy and requires less floor space per application.



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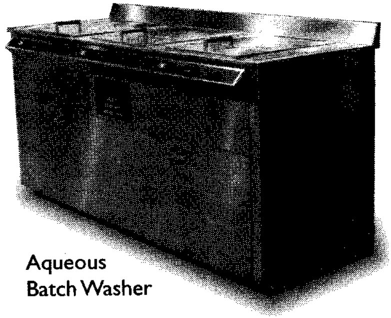

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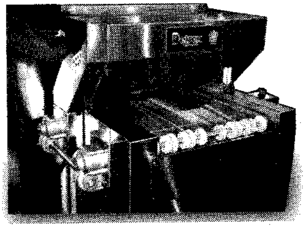

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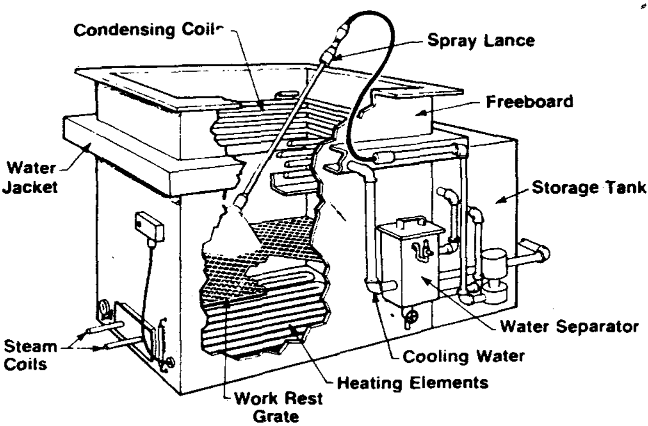

Fig. 1. Conventional open-top vapor degreaser with spray attachment.

Section 612 of the Clean Air Act empowered the EPA to develop a program for evaluating alternatives to ozone-depleting substances. The EPA refers to this program as the Significant New Alternatives Policy (SNAP) program. Under this program, trichloroethylene, perchloroethylene, and methylene chloride are listed as accepted substitutes for 1,1,1–trichloroethane and CFC-113 when used for metal degreasing, precision cleaning, and electronics cleaning applications.

One currently available technology that can effectively use the acceptable substitutes is the enclosed vapor degreaser (EVD). The advanced technology of EVD allows the continued use of the degreasing process safely and in compliance with federal regulations.

It is the EVD design that allows such non-ozone-depleting solvents as trichloroethylene and perchloroethylene to be safely substituted for 1,1,1–trichloroethane and CFC-113. Solvent emission levels from EVDs average less than 10 ppm at all times during the cleaning cycle and when work is being loaded and unloaded from the cleaning system. This is of particular importance, since both trichloroethylene and methylene chloride have TLVs of 50 ppm, with perchloroethylene at 25 ppm (Table 1).

EVD—THE ALTERNATIVE CLEANING SYSTEM

The system design of an EVD is basically simple, but extremely effective (Fig. 2). It consists of the cleaning chamber where all the cleaning operations take place; a boil sump used to generate vapor for cleaning and drying the work; a condensing chamber used to condense solvent vapor into solvent liquid; a carbon adsorption chamber to remove solvent from saturated air; a spray reservoir, which supplies solvent for the spray cleaning cycle; and a water separation device to remove moisture from the condensed solvent.

All of the equipment is housed in a cabinet to form the cleaning system. Pipe and ductwork join the various components of the system together.

When a work load is placed into an EVD, it essentially is being placed into an empty vessel. There is no solvent or solvent vapor present in the work chamber of these systems when the cover is in the open position or when the degreaser is in the idle state. The entire cleaning chamber can be filled with work to be cleaned. In a conventional degreasing system, the work chamber always has solvent vapor present. Because this is the case, the length or the width of the work load must be one-half the length or width of the degreaser to prevent the work load from acting like a piston and pumping out solvent vapor as it enters the vapor zone.

"Our Finishing Equipment vapor degreaser was a major factor in our receiving the EPA's Hammer Award."

Michael P. McMonagle, President
Superior Plating, Inc.
Minneapolis, MN

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Table I. Physical Properties

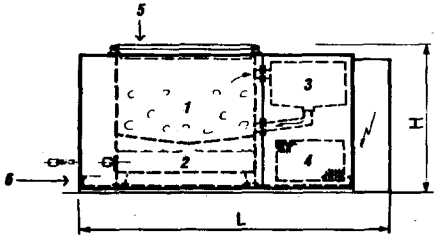
	Methylene Chloride	*Trichloroethylene*	*Perchloroethylene*
Chemical structure	CH_2Cl_2	$CHClCCl_3$	CCl_2CCL_2
Molecular weight	84.94	131.40	165.85
Boiling point, °F (°C)	104 (39.8)	189 (86.9)	250 (121)
Specific gravity, 25°C/25°C	1.316	1.456	1.613
Density, lb/gal at 25°C	10.98	12.11	13.47
Nonvolatile residue, max. ppm	10	10	25
Acid acceptance (as NaOH), min, % wt	0.23	0.17	0.10
Free halogens, ppm	None	None	None
Acidity (as HCl), max. ppm	10	None	None
Flammability limits			
LFL	14.8% (25°C)	8.0 (25°C)	None
UFL	25% (50°C)	10.5% (25°C)	
OSHA (PEL)	500	100	100
ACGIH (TLV)	50	50	25

The cleaning cycle begins by placing the work load into the degreaser, closing the lid, and depressing the start button on the control console. Activating the start button seals the lid, isolating the work chamber (Fig. 2–area 1) from the workplace environment. Solvent from the distillate receiver is then sprayed onto the work surface to aid in the removal of insoluble contaminants. When the spray cycle is completed, solvent vapor flows into the chamber from the boil sump of the system (Fig. 2–area 2). As the vapor enters the chamber, it condenses on the part dissolving the oils and greases. Condensate cleaning continues until the temperature of the parts being cleaned and the vapor temperature reach equilibrium. When equilibrium is reached, the cleaning cycle is completed. At the completion of the vapor cleaning cycle, a refrigerated cooling coil is activated and the solvent vapor present in the cleaning chamber is condensed to a liquid. The liquid is pumped into a distillate receiver and remains there, ready to be used in the spray portion of the next cleaning cycle.

The next step in the process requires the desorption of solvent from a carbon mat medium. This solvent being desorbed was accumulated in the previous cleaning cycle. Desorption takes place by circulating hot air through the carbon purification unit (Fig. 2–area 3), which causes the solvent on the surface of the carbon to release in concentrated form to the hot airstream. The saturated airstream then is directed through a cooling unit (Fig. 2–area 4) and the solvent is condensed out. The desorbed solvent is directed through the water separator and into the distillate receiver.

When desorption of the carbon media is completed, the solvent-laden air volume of the work chamber, which is still sealed, is recirculated through the carbon mat filters to remove solvent from the air. As the solvent/air mixture passes through the carbon medium, it is adsorbed onto its surface. This continues until the solvent concentration of the air in the work

Fig. 2. Enclosed vapor degreaser.



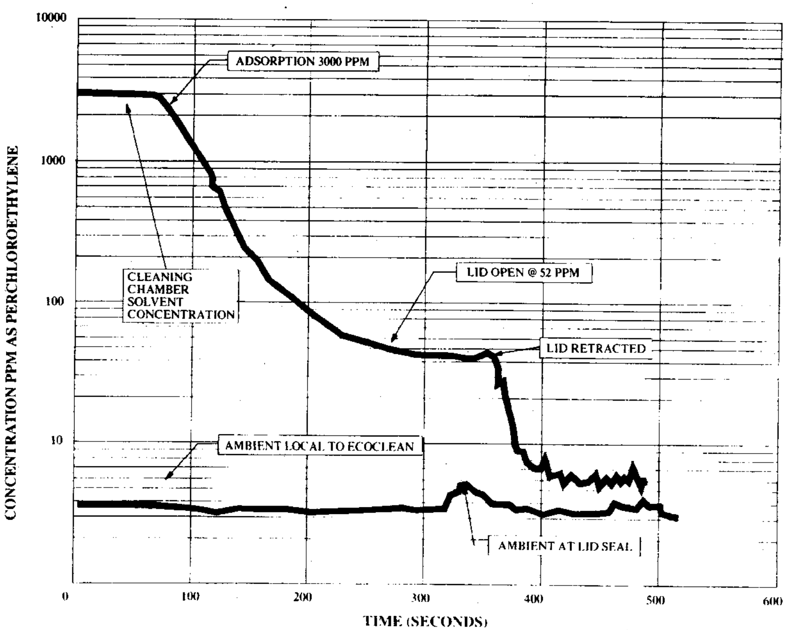


Fig. 3. Fugitive emissions.

chamber reaches 1 gm/m^3. When this level is reached, the entire cycle is completed, the seal on the cover is released, and the work can be removed.

The Battelle Institute was commissioned by the EPA to do a study on enclosed vapor degreasers. The study demonstrated that enclosed vapor degreasers reduce air emissions by 99% when compared with air emissions from typical open-top vapor degreasers. Battelle defined a typical vapor degreaser as having a 0.75 freeboard ratio, a primary cooling coil, electric hoist (to load and unload the degreaser), and no lip exhaust.

Figure 3 (fugitive emissions) shows the relative concentration of perchloroethylene in the work chamber during the cleaning, desorption, and adsorption cycle versus the solvent concentration outside the degreaser at the sealed lid. The high point of concentration at the lip of the degreaser tank was 5 ppm, which occurred when the lid was open at the conclusion of the cycle.

When the amount of oil or soluble contamination of the boil chamber reaches 30% by volume, the machine is placed into the distillation cycle. In this cycle, the solvent is heated in the boil chamber, creating a vapor and leaving the soluble contaminants (oil, waxes, etc.) behind. The vapor is directed through a refrigerated condenser coil and returns to a liquid state. The liquid is temporarily stored in a chamber of the degreaser until the distillation cycle is completed. When the distillation cycle is completed, the remaining contents of the boil chamber are allowed to cool and are then transferred to a suitable chamber and disposed of in accordance with federal, state, and local requirements.

In addition to the EVD just discussed, there are versions that degrease by immersing the work to be cleaned in solvent. Immersion cleaning can be enhanced by adding ultrasonic and injection flood wash agitation. Rotation of the work can also be employed to aid in cleaning and drying. Vacuum can also be employed to aid in the drying of the work.

SAFETY AND HANDLING

Chlorinated solvents have been used for many years with a low incidence of health-and-safety-related problems. The primary routes of exposure are inhalation and skin. Eye exposure is less common and oral ingestion is rare.

Accidental swallowing of small amounts of any of the chlorinated solvents presents minimal hazard, but ingestion of substantial amounts can cause serious injury. To prevent accidental ingestion, always store solvents properly labeled and in containers that will not be mistaken for beverage use. If solvent is swallowed, do not induce vomiting, but obtain medical assistance.

Prolonged and/or repeated skin contact with chlorinated solvents can extract fat from skin tissues and may cause dermatitis. Occasional contact should not produce adverse effects unless solvent is confined to the skin, for example under a ring or inside one's clothing, and cannot evaporate, and which may result in a chemical burn.

It is not likely that the solvents will be absorbed in acutely toxic amounts through the skin. Neoprene or polyvinyl alcohol gloves should be used for solvent handling. If skin contact occurs, flush skin thoroughly with water and wash contaminated clothing before reusing.

Goggles should be worn when handling solvents. Splashing solvent into the eyes will produce pain and irritation, but no serious injury will result. In the case of eye contact, flush with running water for 15 minutes and then seek medical attention.

The greatest potential hazard for exposure is from inhalation. Extremely high vapor levels can cause death. Inhaling excessive amounts of solvent vapor can produce anesthetic effects. These effects, such as lightheadness or dizziness, will occur at varying concentrations and durations of exposure, depending on the solvent used. Physiological injury may result from repeated or prolonged exposure at levels producing anesthetic effects. Excessive inhalation exposure can be prevented by proper engineering and/or ventilation in nearly all operations. Proper protection may require the use of respirators, hose masks, or self-contained breathing apparatus, depending on the operation being performed, when ventilation does not provide adequate protection. In the case of an inhalation exposure, remove the worker to fresh air and get medical attention. Apply mouth-to-mouth resuscitation of respiration stops. Do not administer stimulants, e.g., epinephrine.

Exposure to the vapor of chlorinated solvents at the OSHA/ACGIH exposure limits or less should not cause adverse health effects.

A PROVEN TECHNOLOGY

Enclosed vapor degreasing technology is proven. It has existed in Europe for more than a decade. EVDs are used to clean everything from aircraft parts to cosmetic jewelry containers. The good news it that for those manufacturers who wish to use vapor degreasing or for those who have no choice and must degrease, EVDs allow the process to be used in safety and in accordance with government mandates.

ULTRASONICS—A PRACTICAL APPROACH

by Kenneth R. Allen

CAE Cleaning Technologies, Cincinnati

After reading countless articles on how ultrasonics work, the various aspects of cavitation, and which frequency is better I found that most authors concentrated heavily on the theoretical parameters. The articles had little or no information on the practical side of application. To most manufacturing engineers like myself this does not help them solve their primary problems. How does it get my parts clean? Is ultrasonics right for my application? Can ultrasonic cleaning help me? How does it compare with other types of cleaning?

For these reasons I review theory only briefly. The major focus in this section will be on the application of ultrasonics in parts cleaning, as it compares with other types of cleaning. Where does ultrasonics fit in relationship to other mechanical cleaning such as turbulation or spray washing?

Whether you are trying to improve a plating application, an existing cleaning line, or trying to replace a vapor degreaser, most parameters that will be discussed will apply.

THE THEORY IN BRIEF

How It Works

Ultrasonic cleaning is the introduction of high-frequency sound waves into a liquid, usually between 20 and 80 kHz. The resulting action is called "cavitation." Cavitation is created by high- and low-pressure areas produced in the solution as the sound waves pass through it. In low-pressure areas microscopic vapor bubbles form. The pressure rises rapidly as the next sound wave passes through the area, violently imploding the minute bubbles, releasing the energy that does the cleaning.

The Transducer

This device converts high-frequency electrical energy into mechanical motion. The transducer physically oscillates at its resonant frequency. There are two basic types, magnetostrictive and piezoelectric. Magnetostrictive transducers are metallic, usually made of laminated nickel and are typically silver brazed to a plate. Piezoelectric transducers are composed of man-made crystals and are mounted in various ways, the most common being epoxy bonding.

The Generator

The generator converts low-frequency line power at 50 to 60 cycles per second to high-frequency power (20–80 kHz) that matches the resonant frequency of the transducer. Generators designed to drive piezoelectric transducers often have automatic tuning or frequency controls to compensate for fluctuations in the resonant frequency of the crystal transducer. Typically, magnetostrictive generators do not have automatic tuning because the resonant frequency of the magnetostrictive transducer is more stable.

THE APPLICATION OF ULTRASONICS FOR CLEANING

In general ultrasonics is used in precision-cleaning applications of more complex parts. It has the ability to clean in narrow crevices and small holes that would not be easily

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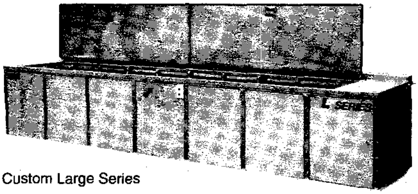

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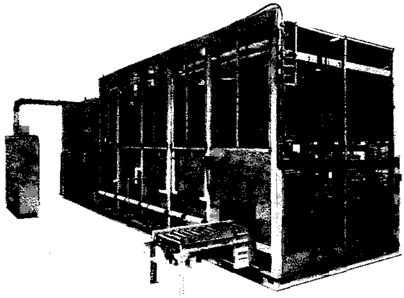

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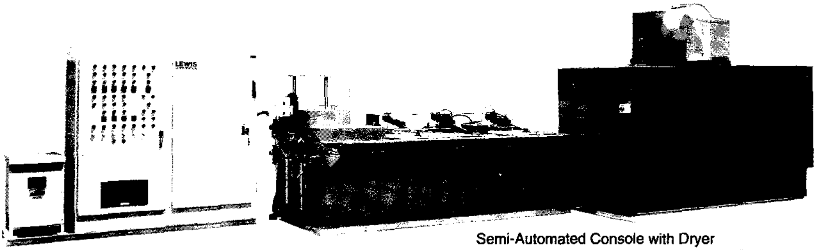

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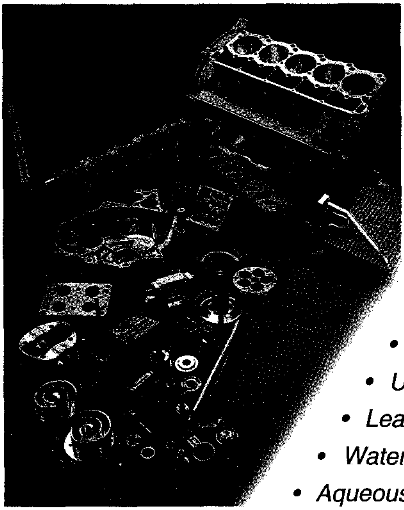
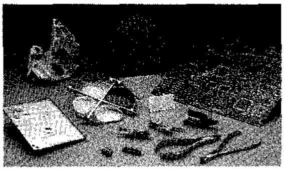




accessible by a spray washer or other methods of cleaning. Difficult soils, such as buffing compounds and baked-on carbon, are also good candidates for ultrasonics. In other words the more complex the part configuration and more stubborn the contaminant, the more likely ultrasonics will be of benefit to the cleaning process.

There are also many other factors that contribute to the cleaning process equation such as the type of soil, chemical limitations, temperature, cycle time, piece part volume, etc. I attempt to illustrate how these parameters interrelate to ultrasonic cleaning.

There are three types of energy available in any given cleaning application: (1) thermal energy, (2) chemical energy, and (3) mechanical energy.

The success of a cleaning application depends on the balance and relationship of these three types of energy. The fourth parameter is time, which increases the effectiveness of all three energies.

Ultrasonics is only one type of mechanical energy. It is only one part of the equation for a successful cleaning process. Other forms of mechanical energy used in cleaning would be simple immersion, spray, turbulation, agitation, and rotation of the part. The selection of the type of mechanical energy depends to a great extent on the relationship of the heat applied to the process and the type of chemistry used. Many times companies only consider the chemical aspects when converting a vapor degreaser, trading the solvent for another chemical. A more successful approach considers all of these parameters, which maximizes the investment.

Ultrasonics is not a magic force, nor is it right for every application. It is just another form of mechanical energy to enhance a chemical process.

Thermal Energy: (1) Acts as a catalyst to enhance chemical energy. (2) Raises the energy level in any type of process. (3) Can condition a contaminant to be acted upon by chemical and mechanical energies, especially ultrasonic applications.

Chemical Energy: (1) Provides a method to break molecular bonds. (2) Acts primarily on organic contamination. (3) Provides many properties to do many jobs, i.e., degreasing, pickling, phosphating, etc. (4) Can be polar (water soluble) or nonpolar (water insoluble).

Mechanical Energy: (1) Provides energy to physically remove contamination from the part surface. (2) Is used to enhance chemical and thermal energy. (3) Is available in many forms, including spray, agitation, turbulation, and ultrasonics.

Using a combination of these energies, and finding the balance for your application, can be a challenging project. The relationship of the chemistry, the temperature of the bath, and the degree of mechanical motion the part can withstand are all critical factors in choosing your cleaning method.

Examples

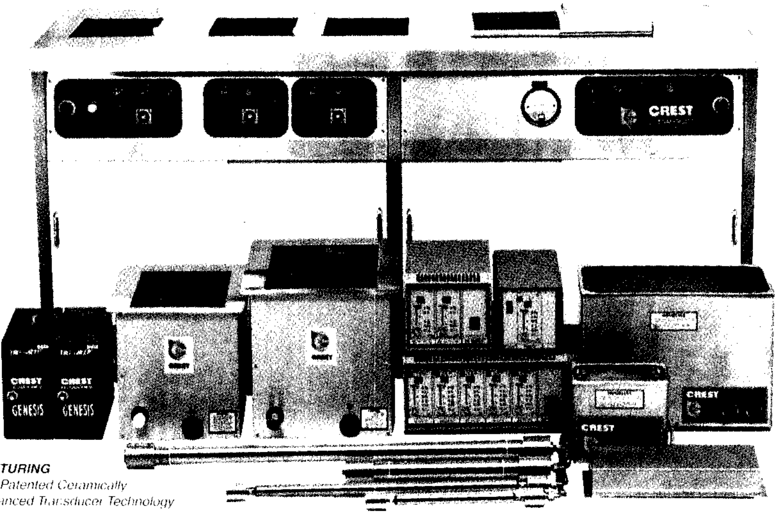
If your part is not complex, made of steel, is not susceptible to mechanical damage, and only contaminated with cutting oil, you probably will not need ultrasonic cleaning. A typical process might look like this:

Temperature, 160°F
Chemistry, pH neutral
Agitation bath with oil separation
Cycle time, 5 min.

Take the same part and add blind holes 2 in. deep by ½ in. in diameter. The process might look like this:

Temperature, 160°F
Chemistry, pH neutral
Turbulation, parts fixtured with a rotating basket and oil separation
Cycle time, 5 min.

If this same part has been sitting around in storage and has corroded, the process might look like this:



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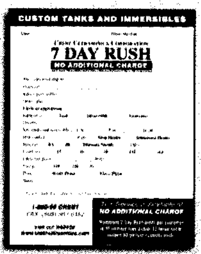

Temperature, 180°F
Chemistry, pH 12.5
Turbulation with rotation, no oil separation
Cycle time, 10 min.

At this point one might need to introduce ultrasonics as the mechanical catalyst in the equation. The cycle is getting long and the temperature is getting high. By introducing a high degree of mechanical action it may be possible to reduce both:

Temperature, 140°F
Chemistry, pH 12.5
Ultrasonic with rotation
Cycle time, 5 min.

REAL LIFE

A manufacturer of aviation hardware was using a vapor degreaser to remove oil and 50% nitric acid at 170°F to deoxidize aluminum parts prior to brazing. By using ultrasonics it was possible to combine both processes in one clean line.

1. Ultrasonic degrease in an aqueous-based solution pH neutral at 140°F.
2. Hot water rinse.
3. 5% citric acid at 140°F with ultrasonics.
4. Deionized rinse at 160°F.
5. Deionized rinse at 160°F.
6. Hot air dry.

The capital equipment cost to the manufacturer was $160,000; however, because of savings in operating costs by eliminating the degreaser and eliminating waste disposal of the nitric acid, the R.O.I. was less than eighteen months. Moreover, this process is much safer and gave the user a dramatic increase in quality.

The main factor in this application is that the ultrasonics allowed this manufacturer to use a much less hazardous acid by adding a high degree of mechanical energy to the process, thereby enhancing a neutral pH bath for thorough degreasing instead of 1,1,1-trichloroethane.

Another example of the successful application of ultrasonics is in plating; especially in reel-to-reel plating of strip. Most plating lines use strong alkalines at approximately 170°F and electrocleaning for soil removal at the beginning of the plating line. In many cases the strip or parts have gone through a vapor degreaser. The problems with this type of cleaning are that it limits line speed, and high pH chemistries are usually not free-rinsing. This causes contamination of the plating baths with carryover and high rinsewater usage. The parts also must be degreased prior to plating because high pH tends to emulsify oil and deplete the chemistry. By using high-intensity ultrasonics most of these problems are eliminated. Ultrasonics is being used in reel-to-reel plating with a pH neutral detergent at 140°F in place of the electrocleaner. Because of the neutral detergent any oil will float and can be separated with a coalescer. This often leads to the elimination of the vapor degreaser prior to plating as well. It is free-rinsing and, in most cases, the line speed can be doubled. The advantages are many: the plating baths do not get contaminated, water usage is cut in half, product quality is more consistent, chemical and waste treatment costs are lower, and output of the line is doubled.

These examples are only two of hundreds like them that illustrate the benefits of applying the proper type of mechanical energy to a process. Table I provides a list of parts typically cleaned in ultrasonic processes.

When trying to determine if ultrasonic cleaning can help you keep these few things in mind:

1. Is the part a complex shape?
2. Does the part have small crevices, blind holes, or deep recesses?
3. Is the part delicate? Will strong agitation damage it?

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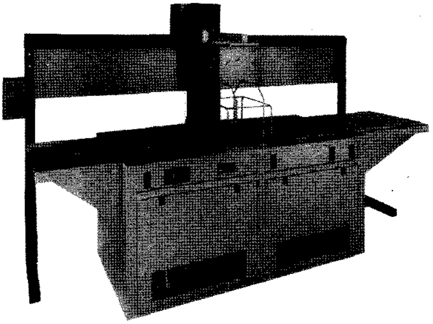

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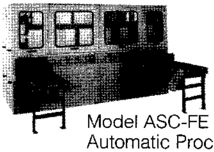

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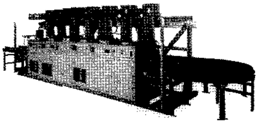

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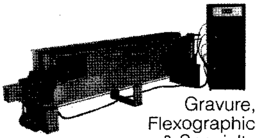

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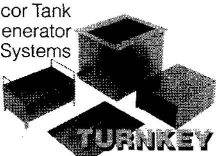

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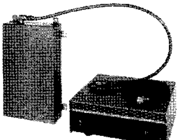

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Table I. Typical Applications for Ultrasonic Cleaning

Diesel fuel nozzles
Turbine engine blade and vanes
Bearings, races, and rings
Aircraft fuel nozzles
Flatware (buffing compound)
Stamped parts (pieces or strips)
Pistons
Piston rings
Valve lifters
Battery cans
Die castings (buffing compound)
Textile spinnerettes
Rachet handles (buffing)
Valve plates, refrigeration
Continuous strips, up to 200 fpm
Golf club heads (buffing)
Computer disk drive hubs
ABS valve bodies

4. Will strong chemistry damage the part? (Example—you cannot use high pH on aluminum).
5. Will high temperature affect the part?
6. Is the cleaning cycle time limited because of part volume?

If the answer to most of the questions is "yes" then you are a candidate for ultrasonic cleaning. Future trends are dictating cleaner parts, better quality, and a safer environment. Ultrasonics can be a tool to help you.

SIZING THE SYSTEM

Once you have determined that ultrasonics is right for your application the next question is "How do I choose the right power level, tank, configuration, etc.?"

It takes a certain amount of energy to achieve the "threshold of cavitation," i.e., the level of energy required to achieve cavitation. The problem is that when you put a load in the tank, you attenuate or absorb energy. If you do not have a good Watt density (power level) you can fall below the threshold, and cavitation ceases. In other words the heavier your load, the more power or Watt density you will need. Some ultrasonic manufacturers calculate in terms of Watt density per area of radiating face such as 5 to 7 W/in^2. Others recommend power levels in terms of volume, typically in 40 to 75 W/gal. Because the displacement of the ultrasonic transducer is a mass relationship a volumetric determination seems more realistic. It is desirable to have the transducer/diaphragm moving mass exceed the mass of the cleaning load. This usually assures sufficient driving energy to compensate for load attenuation.

In most general degreasing applications 40 to 60 W/gal seems adequate; however, in applications such as removing burned-on carbon in turbines or removing a diamond lapping compound, Watt densities of 100 to 150 W/gal are common.

Often the number of transducers seems to be used as a yardstick to measure how much power is in a tank. This is not an accurate method and should not be used to compare manufacturers. Most types of crystal transducers can range from 20 to 50 Watts per transducer. Magnetostrictive transducers can range from 50 to 1,000 Watts per transducer. You would need twice as many of one type to get the same energy in a given volume as another. This is why the W/gal approach is a more reliable method of determining if the power available will be adequate.

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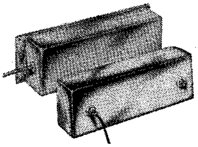

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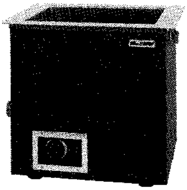

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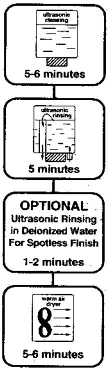

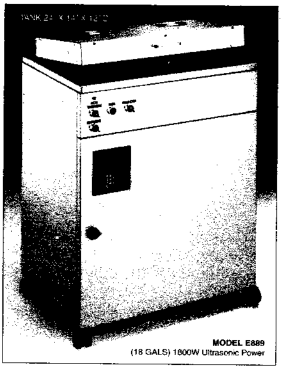

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Trying to determine the size of the tank can be difficult. Trying to scale up any type of manufacturing process can be challenging. If it is possible you should test clean production lots in the laboratory or in equipment to closely approximate the manufacturing environment. Choose a tank size that will adequately accept your part or basket with enough clearance to allow for easy placement and extraction. The other consideration is liquid displacement. As a general rule your part volume should not displace more than 25% of the total tank volume. The reason for this is to maintain enough liquid level to cover the part. You do not want to displace solution out of the overflow weir every time you put a basket of parts in the tank. You will have to constantly add water to maintain a consistent level.

There are two things that are usually overlooked that will greatly enhance any equipment selection. Make sure that the ultrasonic tank has adequate filtration and a sparge/overflow system with oil separation when oil is being removed from the parts. This keeps the floating oil from redepositing on the parts and keeps the particulate level down in the tank. It also has the additional benefit of enhancing the cavitation because high amounts of suspended solids also attenuate (reduce) the ultrasonic activity. The money spent on filtration will be recouped by way of reduced chemical consumption, cleaner parts, more consistent quality, and reduced cycle times. Removing as much oil as possible will give similar benefits. The preferred type of oil separation is usually a coalescing system. Oil wheels work but do not remove oil fast enough in a production situation.

The next thing to consider is an adequate rinse system. "You cannot get clean dishes out of dirty dishwater." The same applies to clean parts. Your part will only be as clean as your final rinse. As a minimum a two-tank cascading system should be considered.

WHEN SHOULD I CONSIDER AN ULTRASONIC RINSE?

Ultrasonic rinsing typically is not considered because of cost considerations. It adds 30 to 40% increased cost to most clean lines; however, if the holes in your part retain water due to capillary action, then an ultrasonic rinse will be required. This is because a heated static rinse will not remove trapped chemicals and debris from tiny capillary holes. Small blind holes are rinsed by diffusion rather than by flushing. Ultrasonics will add the impingement energy necessary to flush these difficult areas. Typical parts that require an ultrasonic rinse are textile spinnerettes, ultra-high-pressure diesel-fuel nozzles, hypodermic needles, and parts that nest or stick together. In a cascading system the ultrasonic rinse should be the final rinse. Again, the best way to make your final process determination is by doing careful laboratory analysis.

Be sure to work with an equipment supplier who can help you develop a process and choose the chemistry and equipment. Most major ultrasonic and cleaning equipment suppliers have laboratory facilities and will do sample parts cleaning for you at no charge. Take advantage of the resources available to you.

AQUEOUS WASHING SYSTEMS

by Edward H. Tulinski

Jensen Fabricating Engineers, Berlin, Conn.

As we enter the new millennium aqueous washing systems have become the dominant method of cleaning in the industrial marketplace as manufacturers strive to become environmentally compliant.

To claim that aqueous systems have come into their own market niche is an understatement. Aqueous systems clean better, meet higher cleanliness tolerances, and perform at higher production rates than traditional solvent cleaning systems. Aqueous cleaned parts are film and residue free.

For an aqueous system to be successful proper equipment and process selection or configuration is necessary. This is best achieved by interaction between the end user and the chemical and equipment suppliers.

DEFINITIONS

It is important that the end user establish some ground rules or definitions that the equipment is to be designed around. The end user must define the following:

Parts

The end user should define the part or parts, their maximum size, and geometry. It also should be determined whether, during the cleaning cycle, parts can come in contact with one another, or whether parts must be maintained in a proper geometry, or even fixtured.

Productivity

The end user must determine the productivity level, in terms of parts per hour, that the system is to generate. If multiple parts are to be processed, depending upon the equipment utilized, the equipment should also be sized and designed to ensure that product flow through the machine does not cause any part mixing.

Material Handling

The end user should discuss how the parts are to come to the aqueous system. The manner of delivery of components, whether they are in baskets, totes, on blue steel, egg crated, or in large hoppers, may determine equipment configuration, as well as the degree and need for automation. Parts can feed into systems directly in bulk, in baskets, or in line.

Acceptable Cleanliness Standard

The end user needs to establish or supply a cleanliness specification. Various types of aqueous systems are geared for large particulate and oil removal only, while other systems are capable of achieving high precision and low mil-pore or low total molecular weight cleaning criteria. By specifying the cleaning requirement this will also help determine the type and the configuration of the aqueous system to be utilized.

Once the end user has defined part geometry, productivity, product delivery, and cleanliness specifications the type of aqueous system to be utilized can be defined.

Mechanical Interaction

The above end-user defined parameters are important to determine the type of mechanical interaction that the aqueous system is to develop. Mechanical interaction is the most important part of system design and can determine the success or failure of the system. Various forms of mechanical interaction can be employed simultaneously. The standard types of mechanical interaction can be defined as follows:

1. Soak
2. Spray
3. Soak and spray
2. Soak with turbulation
3. Soak with ultrasonics
4. Vertical agitation
5. Vertical agitation with ultrasonics
6. Vertical agitation and rotation
7. Vertical agitation and rotation with ultrasonics

The lowest level of mechanical interaction is soaking alone, the highest degree of mechanical interaction is vertical agitation and rotation with ultrasonics. By determining the type of mechanical interaction to be employed, the end user can determine the degree of cleanliness or the cleaning specifications that the machine will be capable of achieving. Other factors to be defined by the end user and the system supplier include the following:

Chemistry

Establish what chemistry is to be employed, its pH and concentration level or ratio, and the ability of the chemistry to interact and remove the soils and oils on the parts. Most chemistries are alkaline and the percentage of chemistry to maintain a uniform process must be controlled.

Temperature

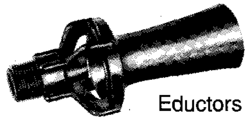
The temperature of the chemistry should be selected so as to ensure that the chemistry is working at its maximum capability. The heat source to maintain temperature and components for spray or pumping loss is to be specified (i.e., electric, steam, or gas). Enough heat is necessary to bring cold parts to temperature for chemical interaction, and for drying.

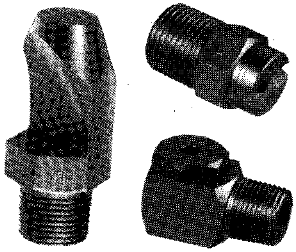
Time

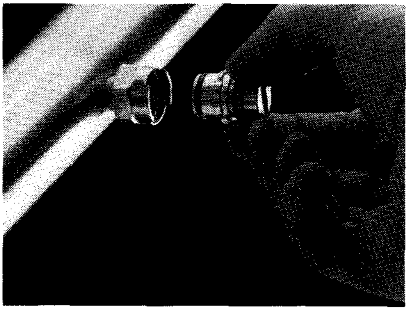
The time should be selected so that the components are involved with mechanical interaction and chemistry to achieve an acceptable production level and an acceptable cleanliness specification.

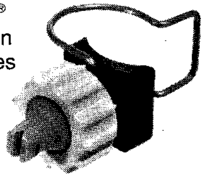
Drying

The drying specification determines how dry components have to be or whether they have to be dried spot free.









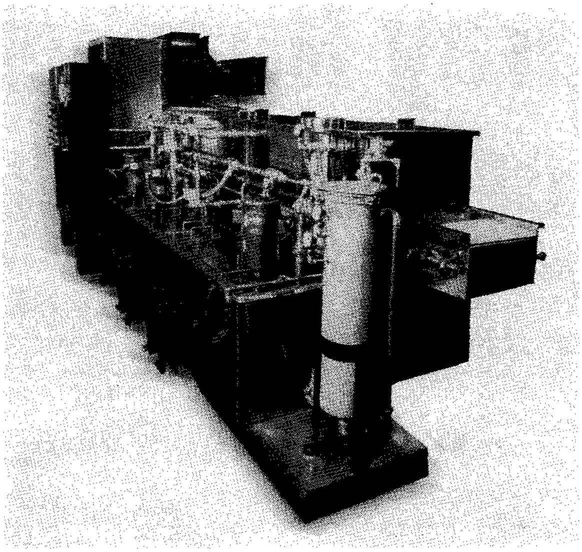


Fig. 1. Belt spray system with wash/rinse/rust inhibit/recirculating hot air dryer, oil coalescor, and wash filtration.

Summary of Cleaning Parameters

In summary, part geometry, productivity, part delivery, and cleanliness specifications are normally defined by the end user. The type of mechanical interaction, the chemistry, its concentration and pH, temperature, time, and drying are normally derived through product testing and interaction between suppliers and end users. It should be understood that satisfying all of these requirements is necessary for the success of an aqueous system. Parts should be tested in large volumes to insure repeatable results.

MECHANICAL ACTION

Since the most important part of the aqueous cleaning cycle is mechanical interaction, the following are some definitions for the standard types of mechanical interaction available.

Soak

Soaking of parts in chemistry relies solely on the mechanical interaction of chemistry to attack, dissolve, and/or emulsify soils. For soak to be successful it is imperative that chemistries be aggressive and that adequate time be utilized to ensure that the chemistry has the ability to interact effectively with soils. Even in soaking, some form of part movement normally takes place as parts are either introduced to a soak tank or withdrawn. It is likely that this small amount of mechanical interaction or part movement will, in effect, do more work than the soak cycle itself.

Spray

Spray is a widely used form of mechanical interaction in aqueous systems. Spray is used on belt systems, monorail systems (see Figs. 1 and 2), cellular and centralized washers, and

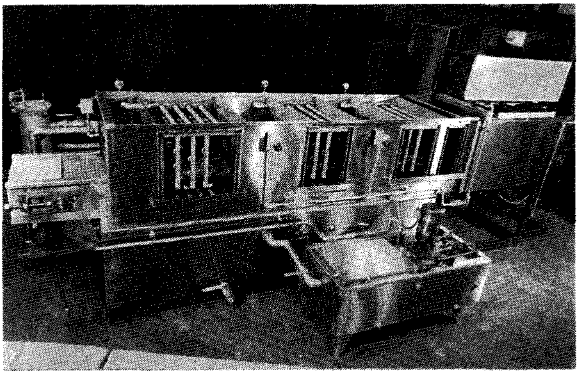


Fig. 2. Access covers from Fig. 1 removed to view spray headers.

with cabinet systems that used low-, medium-, or high-pressure delivery of solution.

Spray systems are designed to direct solution so that it impinges the parts from above, from the sides, and from below. The solution is normally directed by spray headers utilizing nozzles to generate overlapping spray patterns. Parts are typically drawn through spray zones by some form of conveyance, such as belts, monorail, rotating turntable, or rotating baskets. The spray solution is designed to impinge the part surfaces at pressure and high volume. Spray impingement loosens and removes soils. It is necessary to understand that high volume is as important as high pressure, as it is the volume of solution that causes dirts and soils that are removed by the spray impingement to float away or be removed from the parts. The combination of pressure and volume, in conjunction with heated chemistry, is effective in removing soils, oils, dirt, chips, and other by-products associated with manufacturing.

In most cases spray can only be delivered from four axes, while most parts have a minimum of six geometric axes. Likewise, spray can be easily deflected. Spray is not well suited for cleaning blind holes or complex geometries. If parts are processed in baskets, parts positioned on the outside may mask effective cleaning of other components in the middle of the basket, as parts on the surface of the basket will be the ones effectively engaged by spray while parts in the middle of the basket must rely on solution volume and drippage for effective cleaning. For this reason parts in baskets in cabinet cellular washers are rarely filled more than 60%. This allows parts in the middle of the basket to eventually migrate to the exterior of the basket, if the basket is rotated.

Spray systems can also be used as in-line manufacturing cleaning systems. The same belt that it used to transport the parts through the washer can transport parts from one location to another location, thus acting as a material handling unit.

Spray systems should also be designed to ensure that the various spray chambers are shrouded with baffles, both before and after spray zones, to minimize overspray and solution drag-over. A belt can act as a natural pump and adequate drain area is necessary on belt systems to minimize carryover of wash solution to rinse zones, or as the belt returns, from rinse to wash zone. In all instances where spray systems are employed, sufficient drain area or drain cycles are required to allow the parts, belt, and baskets to adequately drain to minimize contamination of subsequent spray zones or to maintain rinse tank clarity.

Soak and Spray

Belt or monorail systems can be equipped with soak zones, these being areas where the part is drawn through a soak stage prior to being sprayed. The soak area will ensure that all

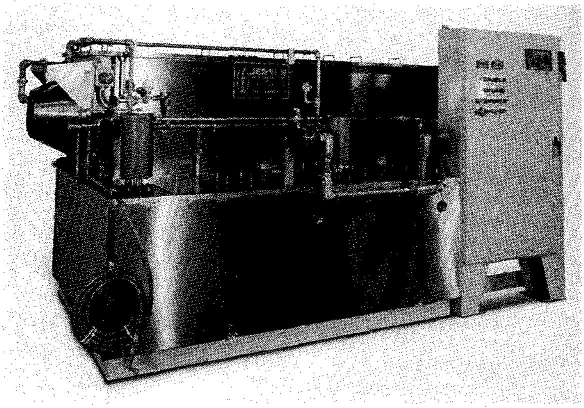


Fig. 3. Rotary drum system, wash, rinse, dry with soak, and spray zone.

areas of the component are exposed to chemistry and can initially loosen and emulsify some soils and oils as parts are drawn through the soak zone, prior to spray impingement. This greatly assists the ability of the spray to flush and remove soils. Rotary drum systems also typically employ soak and spray.

Rotary drums are designed to move parts through various operations in a horizontal cylinder, the interior of the cylinder equipped with a helix (see Figs. 3 and 4). This automatically advances parts forward as the drum rotates and allows a large quantity of parts to be effectively engaged by the mechanical interaction generated by the machine; this a combination of soak and spray impingement, as well as high volume of solution delivery. The parts are soak cleaned and spray cleaned simultaneously. Spray headers are positioned so that the spray engages the parts as they are lifted out of the soak solution. After the soak section, the parts continue to be engaged by spray. The spray typically uses a combination of spray impingement and high-volume solution delivery. The soak section loosens contaminants. The

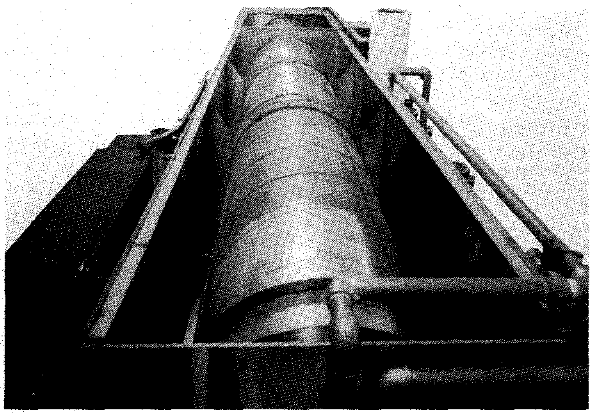


Fig. 4. Rotary drum system with top drum enclosure cover totally removed. Solid drum section is used for soak and spray. Perforated sections for spray and drain.

ACTION!

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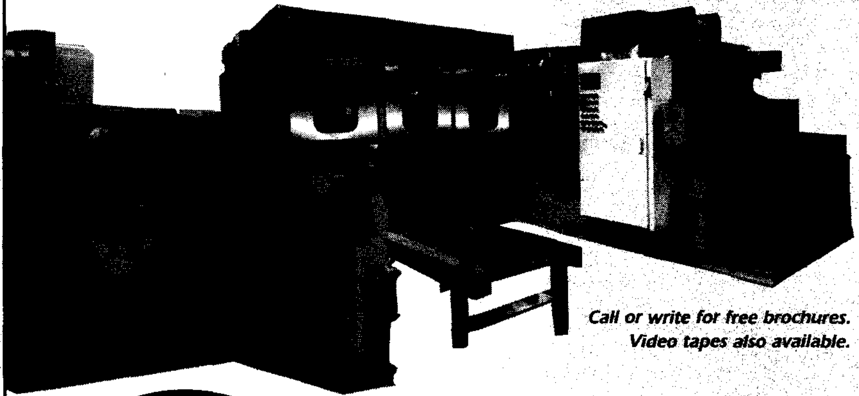
From edge-to-surface-to-edge, around contours and through holes, JenFab Cleans, rinses and dries parts to your specifications. We guarantee it, with proper equipment selection. Our line of automated, in-line aqueous vertical, agitation and rotation, continuous rotary, belt, monorail and combination systems are the industry's most extensive.

JenFab Continuous Rotary Systems handle large volumes of parts. The gentle, tumbling action of the rotating cylinder exposes all surfaces to the soaking and high pressure spray cleaning solution. Rotary systems are equally effective for all types of wash, rinse, phosphating, bright dipping and drying action. Systems with drums up to 60 inches in diameter are available. Vertical Agitation/Rotation Systems clean with a hydraulic flushing and scrubbing action that reaches between parts, and along their surfaces into recesses, cavities and holes. Oil, grease, metallic fines and chips are effectively removed. Automated systems handle parts in baskets, racks or barrels. Tank sizes from 60 to 3000 gallons can process loads from 50 to 3000 pounds per hour. Optional ultrasonics packages offer even greater cleaning power.

JenFab... It's all in the action!



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high-pressure spray impingement is generated by directed stainless steel spray nozzles and is designed to dislodge contaminants from the parts. In short the combination of soak and spray impingement dislodges soils; the high-volume delivery flushes the soils, oils, and other contaminants away.

In a rotary drum system the mass of parts is gently tumbled in the aqueous cleaning and rinsing solutions. This gentle tumbling action provides an effective method of completely exposing all edges and surfaces of components to the action of the soak, impingement spray, high-volume solution delivery, rinsing solutions, and to the drying action. The rotation of the drum causes parts to rotate and move. The movement within the drum causes all surfaces and edges to be exposed to the cleaning action; therefore, all areas of parts are engaged by the cleaning capability of the system. It is the combination of part movement, immersion, high-pressure spray, and high-volume solution delivery that is more effective than spray alone in dislodging contaminants and soils from all areas of the parts.

Parts do contact one another in a rotary drum system. If no part contact is permitted this would not be a system of choice.

Soak with Turbulation

Turbulation is, in essence, exciting the cleaning bath; that is, causing fluid movement within the bath. This is accomplished by using either aerators or impellers to cause the cleaning solution to become a fluidized bed of continuous movement. When parts are introduced to a turbulated bath, the solution moves around areas of the components. This rapid movement of solution has the ability to emulsify oils and dislodge soils.

In turbulated systems care should be taken to ensure that parts do not mask one another. Turbulation moves tremendous volumes of solution but lacks any driving force to penetrate a basket or a layer of parts. This masking is sometimes offset by ensuring that there is part movement in the turbulated bath. Part exposure to turbulation is accomplished by either rotating or articulating the part. Small components placed in baskets require this rotation movement. The basket itself and the parts in a basket will act as a mask for the turbulation solution. By rotating the basket, parts in the interior of the basket may eventually be drawn or positioned at the exterior of the basket where they may be somewhat engaged by the turbulated solution; therefore, full baskets or even baskets three quarters full of parts cannot be effectively cleaned with turbulation due to no or minimal part movement. Similar to a rotary drum system there is some part-to-part contact due to partially full baskets that are typically rotating.

Turbulated systems like spray are not effective for cleaning ID or blind hole areas.

Vertical Agitation and Rotation

Vertical agitation develops the highest degree of mechanical interaction between parts and chemistry. The vertical agitation movement produces a natural hydraulic cleaning action, generating cavitation in the tank, which forces the cleaning solution between parts and in/out of recesses and cavities. This vertical agitation movement of parts in an aqueous solution generates a flushing action that scrubs all parts surfaces, crevasses, holes, and recesses clean. The agitation movement forces solution between components and in/out of holes.

Parts in many instances are cleaned in baskets (see Figs. 5 and 6). But unlike spray or turbulation systems, parts in baskets do not mask themselves, allowing full baskets of components to be effectively cleaned due to the agitation movement. The mechanical action of agitation removes oils and greases, while loosening and removing metallic fines and chips. One hundred percent immersion of baskets in and out of solution is much more effective than partial immersion.

Adding rotation to the agitation further enhances this capability by allowing all holes, recesses, and cavities to fill and drain effectively with the aqueous chemistries.

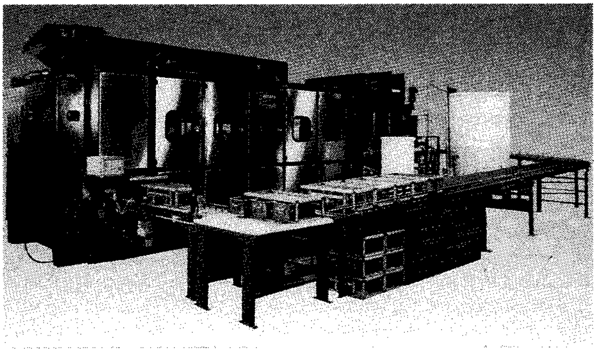

Fig. 5. Five-tank vertical agitation and rotation system with material handling and closed-loop wastewater treatment system. System utilizes a wash, ultrasonic wash, three counterflow rinses, and rotation of baskets in a recirculation hot-air dryer.

With the vertical agitation concept, the amount of agitation can be adjusted for each tank in a process. With the advent of programmable controllers, systems can be programmed to agitate and rotate baskets under solution while occasionally raising the baskets out of solution to drain, then totally immersing the baskets in solution again. Baskets can effectively rotate out of solution for complete draining prior to transfer to subsequent tanks. This drain cycle greatly reduces chemistry drag over and prolongs rinse tank clarity. Vertical agitation systems are also very effective for chip removal, as turbulation can also be added to vertical agitation systems. The turbulation in vertical agitation systems serves a second purpose. The turbulation keeps chips and fines in suspension in the solution until they can be evacuated by high-volume pumps and filters.

The vertical agitation movement also makes this concept readily adaptable for use with ultrasonics. The agitation can be programmed to move slowly up and down while moving through a focused ultrasonic field. This slow up-and-down movement exposes the entire

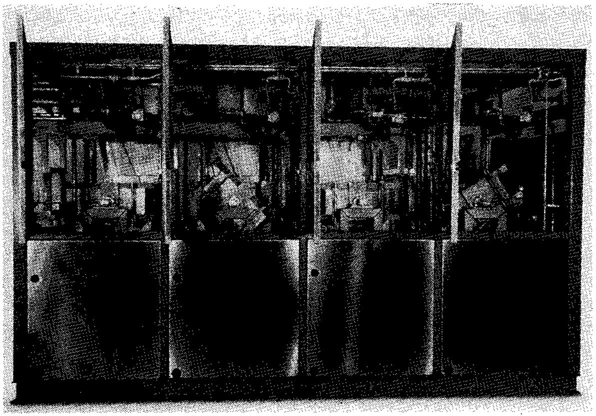

Fig. 6. Vertical agitation and rotation system with access doors open. System agitates baskets 24 in. × 24 in. × 12 in. through a prewash, wash, and two counterflow rinses prior to dry.

workload to the full power of the ultrasonic scrubbing action, allowing full cavitation, generated both by ultrasonics and agitation, to effectively engage components. In agitation systems, ultrasonics are sidewall, bulkhead mounted. This will guarantee that the parts will pass through the high-concentration ultrasonic field. Slow rotation through the ultrasonic field also ensures 100% exposure, allowing blind holes to be effectively filled with solution and engaged with the ultrasonic energy.

Drying

What differentiates an aqueous system from solvent-type systems is the need to dry components. Newer type dryer designs incorporate the principles of high-velocity and high-volume recirculating hot air. High-volume air dries more effectively than high pressure or high temperature, and dryers should be designed to allow for maximum air movement at minimal operating temperature. Systems that employ high temperature to flash dry parts can cause spotting on components and discoloration of certain alloys.

Good dryer design employs louvers that will direct the air flow directly against the components and baskets, if they are employed. The dryer design should contain an internal duct system that directs the air flow from multiple directions against the parts or baskets. This design will ensure uniform exposure of all surfaces, edges, and recesses of components to this air flow.

As with interaction of chemistry with components, time is a variable in the drying process and end users should be aware that shortening dryer time to save space can be detrimental and compromise the effectiveness of dryer design.

On belt- or monorail-type systems, air knives can be used prior to drying to remove puddled water from recesses and cavities. Air knives are important when parts cannot rotate, either prior to or in the drying process.

Air knives on belt or monorail systems can also be used between wash and rinse stages to minimize cross-tank contamination. This will effectively remove chemistry residues from the belt as well as parts. Newer style air knives can employ either low pressure and volume shop or self-generated air-style delivery systems.

THE AQUEOUS PROCESS

Most aqueous processes require, as a minimum, a wash, a rinse, and a dry. There may be multiple wash and rinse stages, depending upon the desired cleanliness level.

Typically, wash requires a mild alkaline cleaner that is heated. Care should be taken in the selection of the cleaner to ensure that it is compatible with alloys being cleaned and has the ability to emulsify or split oils and remove other contaminants.

The purpose of rinses is to remove residual chemistry remaining on parts. If only one rinse is employed, a flow of clean water into the rinse tank on a continual basis to an overflow dam is necessary to maintain rinse clarity. A system employing two rinses should consume half the water that a single-rinse system will require. Likewise, three rinses will utilize half the water that a two-rinse system will use to maintain final rinse tank clarity. Depending upon cleanliness specification and whether spot-free drying is necessary, RO or DI waters may be necessary for final rinses.

If RO or DI water is employed consideration should be made to prevent flash rusting on ferrous components. It may be necessary to add rust inhibitors or wetting agents to rinse tanks to prevent flash rusting while rinsing ferrous components.

WATER QUALITY

If incoming municipal waters contain a high level of chlorine, sulfur, salts, or other contaminants it may be necessary to treat this water prior to use. Water hardness and poor quality of water can affect the ability of the aqueous chemistries to work. Likewise, poor water quality can affect drying and cause water spotting.

SYSTEM CONSTRUCTION

All aqueous cleaning systems should be constructed with stainless steel for tanks and wetted surfaces. Whereas mild steel construction was acceptable in the past the greatest cost factor in manufacturing an aqueous system is labor. Stainless steel, although three times the cost of mild steel, should have a cost impact of less than 20% on the overall system. Mild steel construction will always oxidize in time and cause degradation of baths, compromise the ability to clean, and cause rinsewater to always contain ferrous oxides. Stainless steel construction overcomes these shortcomings and should give an aqueous system a minimal 20-year life.

FILTRATION

Filtration will greatly prolong bath life and allow for a more uniform cleaning process. Aqueous chemistries are designed to remove soils. Most chemistries are designed to emulsify or suspend soils in the wash bath. In time these soils will build up in the wash bath.

For spray-type systems filtration should be inline between pump and spray headers. Filters should be constructed of stainless steel and sized to be, as a minimum, 20% above pump volumetric flow rate.

For bath-type systems filtration should be designed to exchange the total volume of the bath every three to five minutes. A tank bath of 200 gal should have, as a minimum, a 40 gpm pump and 50 gpm filter system. Filtration is designed to remove suspended finds, particulate, soils, dirt, etc. Good filtration will prevent redeposit of the soils on the parts.

OIL REMOVAL

Most chemistries are designed to split petroleum and tramp oil and cause the oil to float to the tank surface. Many types of oil removal systems are available and vary in price, complexity, and efficiency. Disk, belt, and decant systems are marginally effective. Coalescing and ultrafiltration are the most effective. Coalescing systems with surface skimmers or spargers are required for bath or agitating systems to ensure that the top surface of the water is free of oil prior to the removal of parts.

Oil coalescers are normally freestanding units constructed of stainless steel. A coalescer is designed with perforated partitions, making it multiple tanks. The first area is a still tank. The second area is normally filled with polypropylene tubes. The polypropylene tubes are efficient in their ability to collect oil. The tubes attract oil globules to as small as 20 micron. When the oil globule builds and reaches a dimensional size of between 100 and 200 microns it breaks free from the polypropylene tube and floats to the surface of the tank where it is skimmed; therefore, the coalescer is effective in removing oil as small as 20 micron. The coalescor collects only oil and not water and chemistry.

The coalescer then pumps clean water to a sparger pipe positioned to skim the top surface of the tank to an overflow weir. The overflow weir is connected to the coalescer and the system operates as a closed loop.

Emulsified oils must be handled differently. Membrane or evaporation technologies must be incorporated to deal with the emulsified oils in a solution bath.

WASTE TREATMENT

Alkaline chemistries and rinsewaters, by themselves, are normally not an environmental issue. Chemistries are designed to remove soils and oil from parts. If the soils are heavy-metal laden they will have to be treated accordingly. If petroleum-based oils are used, coalescing and other oil-extraction systems can readily remove these oils from baths prior to discharge.

If emulsified oils are present in the bath these will have to be dealt with as regulated by local EPA authorities. Either evaporation or membrane technologies, such as ultrafiltration, should be employed to remove emulsified oils prior to solution discharge to drain.

Normally rinsewaters are sufficiently free of heavy metals and emulsified oils and may be readily dischargable.

In summary local sewer authorities may dictate the type of treatment required for alkaline baths and how these baths are to be disposed. In all instances cost of disposal is normally far less costly than dealing with or disposing of solvents.

EQUIPMENT SELECTION

As stated previously end users have to define part geometry, productivity, material handling, and cleanliness specification. Once these are known tests can be conducted to determine which type of system and the type of mechanical interaction that is best suited to meet end users' needs. Although cost is always a consideration to determine the proper selection of the type of aqueous cleaning system to be used, capability should be the driving force in proper equipment selection. It is important that the system achieve cleanliness specifications at the production levels desired.

Good interaction must be achieved between end user and the equipment supplier to ensure that any proposed system is equipped with adequate mechanical interaction to achieve the desired level of cleanliness, that there is adequate rinsing to ensure removal of residual chemistries with a minimal level of acceptable water usage, and that dryer design will achieve the level and quality of dryness desired.

The equipment costs for aqueous systems normally are higher than solvent systems, but the operating costs are normally less. The purchase costs for aqueous chemistry and chemistry disposal is a small fraction of the purchase and disposal cost of solvent-based chemistries.

In summary aqueous cleaning systems have come of age. They can more effectively clean to a higher cleanliness level than is achievable with solvent systems. Aqueous systems leave no residue on parts.

Aqueous systems are environmentally friendly, end-user friendly, and can consistently achieve desired results.

Aqueous systems offer a cleaning solution and are considered environmentally compliant. With new EPA guidelines and restrictions you can be assured that aqueous systems will become even more dominant in the 21st century.

PICKLING AND ACID DIPPING

by Earl C. Groshart

Consultant, Seattle

Metals can be immersed into solutions of acids to remove metal, metal oxides, heat-treat scale, and foreign metals. Such treatments generally leave the surface chemically clean and ready for further processing.

The general process is to solvent, emulsion, or alkaline clean the parts prior to acid immersion, so that the acid solutions will wet and/or etch uniformly. The part should be free of water breaks after the alkaline step and should remain so throughout processing.

Parts should be racked so that they can be completely immersed in the pickling solution to avoid an air/solution interface where preferential etching can occur; they do not strike or touch each other; there is free draining and rinse water can contact all surfaces; and there are no solution pockets, which prevent complete solution contact, but provide a solution/air interface.

Assemblies containing overlapping surfaces, such as riveted joints, and assemblies containing more than one metal, such as an aluminum assembly with cadmium or stainless steel inserts, should be avoided, or the dissimilar metal should be masked off.

Pickling of two alloys of the same material at one time should be checked to ascertain that galvanic effects will not cause preferential etching of one of the alloys. Processes utilizing hexavalent chromium or cyanide have not been used in the formulas in this chapter. Both of these materials are on the EPA list of hazardous materials to be reduced.

ALUMINUM AND ALUMINUM ALLOYS

Pickling

Mild acid etching of wrought materials to remove heavy oxides, corrosion products, and heat-treat discoloration, can be accomplished by immersion in various combinations of sulfuric, nitric, and hydrofluoric acids or in alkaline solutions. The following solutions are typical:

	Make-up	*Maintenance*
Nitric acid	25% vol	25–30 oz/gal
Hydrofluoric acid	1% vol	To maintain etch rate
Temperature		Room
Etch rate		0.0015–0.003 in./side/hr

Maintenance of etch rate can be accomplished by addition of hydrofluoric acid or ammonium bifluoride.

	Make-up	*Maintenance*
Sodium hydroxide	17.5 oz/gal	16–20 oz/gal
Sodium sulfide	3.0 oz/gal	1.5–3.5 oz/gal
Triethanolamine	6.4 oz/gal	4.0–8.0 oz/gal
Aluminum (scrap)	2.5 oz/gal	2.5–10 oz/gal
Temperature	—	60–90°F
Etch rate	—	0.001–0.008 in./side/hr

Note that dissolving aluminum scrap may require additional NaOH to maintain the etch rate.

Heavy metal removal and brightening of both wrought materials and castings may be accomplished by immersion into a solution of:

Sodium/potassium hydroxide	2–10 oz/gal
Temperature	Room–180°F
Time	To desired etching

The etch rate depends on the concentration of the solution and on the temperature. Higher temperatures and low concentrations are desirable.

The smut that forms on wrought materials of 2000, 7000, and sometimes 6000 series alloys can be removed by immersion in the nitric/hydrofluoric solution indicated above. The smut or black to brown film formed on castings can be removed by dipping in a concentrated nitric acid solution containing some fluoride, as follows:

Nitric acid	75% vol
Hydrofluoric acid	25% vol
Temperature	Room
Time	1–2 min for sand castings 15–30 sec for others

This solution may be used to treat castings whether they have been etched or not and is an excellent method of opening porosity prior to sealing operations.

Removal of foreign metals from aluminum parts, especially lead from parts formed on lead or kirtsite dies, may be accomplished in the following solution:

	Make-up	*Maintenance*
Nitric acid	25% vol	20–35 oz/gal
Sodium dichromate	3.25 oz/gal	2.5–4.0 oz/gal
Molybdic acid	0.5 oz/gal	0.3–0.6 oz/gal
Temperature		120–150°F
Time of immersion		5–10 min

Bright Dipping

The following solutions will remove oxides and corrosion products without etching the aluminum:

	Make-up	*Maintenance*
1. Tragacanth gum	0.5–1.0 oz/gal	—
Hydrofluoric acid	4.5–5.0% vol	4–6 oz/gal as HF by analysis
Temperature		Room

Add the gum tragacanth to denatured ethyl alcohol to make a thin paste. Add the paste to the tank filled with water heated to 180–212°F. Cool the tank to room temperature, then add the acid.

	Make-up	*Maintenance*
2. Hydrofluoric acid	4% vol	1.2–1.6 oz/gal as H_2SiF_6 by analysis
Wetting agent	0.1 oz/gal	0.06–0.1 oz/gal
Temperature		Room
3. Phosphoric acid	80% vol	Dump when no longer effective
Nitric acid	5% vol	Dump when no longer effective
Acetic acid	5% vol	Dump when no longer effective
Water	Remainder	
Temperature		To 220°F

CADMIUM

Pickling

To remove heat discoloration from cadmium, 1% solutions of sulfuric acid or nitric acid will be found effective. Immersion in these solutions will activate the parts prior to chromate conversion treatment. Use the acid that is common with the conversion coating without rinsing between steps.

Bright Dipping

The following solutions may be used:

	Make-up	*Maintenance*
1. Nitric acid	1% vol	—
Temperature		Room
2. Sulfuric acid	1% vol	—
Temperature		Room

COBALT

See Nickel.

COPPER AND COPPER ALLOYS

Pickling

The removal of scales from copper alloys can be accomplished in solutions of sulfuric acid and, where the scales are heavy, by adding an oxidizing acid. The following solutions are examples:

1. To remove heavy scale (red or fire scale):

	Make-up	*Maintenance*
Sulfuric acid (66° Baumé)	32% vol	55–80 oz/gal
Nitric acid (40° Baumé)	12% vol	10–15 oz/gal
Temperature		Room
Copper		3 oz/gal max.

2. For moderate scales:

	Make-up	*Maintenance*
Sulfuric acid (66° Baumé)	12% vol	20–30 oz/gal
Citric acid	5 oz/gal	3–5 oz/gal
or		
Sodium citrate	8 oz/gal	4.5–8.0 oz/gal
Temperature		Room
Copper		2.0 oz/gal max.

3. For light scales:

	Make-up	*Maintenance*
Sulfuric acid (66° Baumé)	10% vol	19–26 oz/gal
Temperature		Room to 125°F
Copper		Up to 4 oz/gal

Alloys that contain more than 0.7% lead can be treated in a fluoboric acid solution, either as a supplementary treatment to remove smut after pickling in the above solutions, or as an oxide (tarnish) remover prior to plating:

	Make-up	*Maintenance*
4. Fluoboric acid (49%)	25% vol	15–24 oz/gal
Temperature		Room
Copper		1.5 oz/gal max.

By adding up to 5% hydrogen peroxide, the bath may be used to remove excess solder from parts prior to mechanical treatment.

Copper-clad laminants to be used for circuit boards may be pickled in the following solutions:

	Make-up	*Maintenance*
5. Ammonium persulfate	32% vol	—
Temperature		Room to 100°F max.
Etch rate	Discard the solution when the rate drops below 30 microin./min	
6. Nitric acid (40° Baumé)	30% vol	30–36 oz/gal
Phosphoric acid (75%)	15% vol	20–25 oz/gal
Temperature		Room to 100°F max.
Copper		1.5 oz/gal max.

Bright Dipping

Solutions 4, 5 and 6 under Pickling will act as effective bright dips, however, the following solutions may be considered:

	Make-up	*Maintenance*
1. Sulfuric acid (66° Baumé)	44% vol	90–110 oz/gal
Nitric acid (40° Baumé)	22% vol	20–25 oz/gal
Water	33% vol	—
Sodium chloride	0.25 oz/gal	

The chloride adds luster to copper; however, excess can cause spotting.

	Make-up	*Maintenance*
2. Phosphoric acid (85%)	55% vol	
Nitric acid (40° Baumé)	20% vol	
Acetic acid (98%)	25% vol	
Temperature		130–175°F

Discard when the solution absorbs water and becomes an etching solution.

Matte Finishing

Copper alloys may be etched in the following solutions to provide a matte or dull finish.

	Make-up	*Maintenance*
1. Hydrochloric acid	50% vol	Discard when ineffective
Ferric chloride (40° Baumé)	50% vol	
Temperature		Room

After etching and rinsing, parts may need a bright dip to remove the smut, which forms on some alloys.

	Make-up	*Maintenance*
2. Sulfuric acid (66° Baumé)	5% vol	10–13 oz/gal
Ferric sulfate	13 oz/gal	10–13 oz/gal
Temperature		Up to 140°F

GOLD AND GOLD ALLOYS

Gold alloys can be brightened by anodic treatment at 6–12 V in solutions in which gold is soluble. The following solutions are examples:

	Make-up	*Maintenance*
1. Sodium citrate	20 oz/gal	16–20 oz/gal
Rochelle salts	5 oz/gal	3–5 oz/gal
2. Sodium hydroxide	to pH 7	pH 6–8
Temperature		150–175°F
3. Sodium hydroxide	4 oz/gal	3–4 oz/gal
Sodium carbonate	2 oz/gal	—
Disodium phosphate	2 oz/gal	1–2 oz/gal
Temperature		150–170°F

Gold can be recovered from the baths by low current electrolyzing onto stainless steel cathodes with stainless steel anodes.

IRON AND STEEL

The usual solutions for the removal of scale and rust from iron and steel products are hydrochloric or sulfuric acids. These are used in concentration ranges from a few ounces per gallon to very concentrated, depending on the type of work being processed. Cold-rolled steel (CRS) can be pickled rapidly in weak hydrochloric acid, whereas heavily scaled construction plate is best pickled in concentrated sulfuric.

Commercial inhibitors—amines and nitrates—are common and are optionally used in these pickles to prevent overetching and to avoid pitting. Satisfactory formulas include:

	Make-up	*Maintenance*
1. Hydrochloric acid (20° Baumé)	55% vol	23–40 oz/gal
Inhibitor (optional)		As required
Temperature		Room
Time		0.5–5 min
Iron		Up to 5 oz/gal
Copper		0.5 oz/gal max.
2. Sulfuric acid (66° Baumé)	25% vol	50–65 oz/gal
Inhibitor (optional)		As required
Temperature		Room to 120°F
Time		Up to 10 min

Solution may be used with lead-lined tanks and lead heating coils.

Alloy Steel, 400 Series, and PH Hardened Steels

These steels may be pickled in hydrochloric solutions (see solution 1 above), for 1–10 minutes for heavy scales, and no more than 5 minutes for light scales.

Other solutions particularly suited to the 400 series and PH steels are as follows:

		Make-up	*Maintenance*
3.	Ferric sulfate (anhydrous)	13.5 oz/gal	8.5–13.5 oz/gal
	Hydrofluoric acid (70%)	1.7% vol	1.5–2.5 oz/gal
	Temperature		125–135°F
	Time		1–5 min
4.	Sodium chloride	4 oz/gal	2–4 oz/gal
	Sulfuric acid (66° Baumé)	10% vol	17–27 oz/gal
	Temperature		160–180°F
	Time		1–5 min
5.	Sulfuric acid (66° Baumé)	1% vol	2–3 oz/gal
	Potassium nitrate	3 oz/gal	2–3 oz/gal
	Temperature		160°F
	Time		5–15 min
6.	Potassium permanganate	12 oz/gal	8–12 oz/gal
	Sodium hydroxide	12 oz/gal	8–12 oz/gal
	Temperature		160°F to boiling
	Time		Up to 30 min

Solution 6 is used to loosen heavy scale and should be followed by pickling in solutions 1 or 2 above.

Molten Salt Descaling

Molten salt baths are available for descaling steel and stainless steels. They are proprietary and operate in the temperature range 400–1,000°F. They do not attack the base metals and are particularly useful where heavy scales must be removed and acid solutions sometimes attack the basis metal in preference to the scale leaving it etched and pitted.

Cast Irons

Cast irons can be pickled in solutions that combined sulfuric acid with other acids.

		Make-up	*Maintenance*
7.	Sulfuric acid (66° Baumé)	5–10% vol	10–15 oz/gal or 25–30 oz/gal
	Nitric acid (40° Baumé)	5% vol	4–5 oz/gal
	or		
	Hydrofluoric acid (70%)	10% vol	12–15 oz/gal

Bright Dipping

Bright dipping of steel is not generally satisfactory. For brightening, electropolishing at high current densities is recommended.

Solutions containing citric acid (10–12 oz/gal), to which ammonia is added to produce a pH of 6.5–7, and which are used at boiling, will brighten CRS without removing metal. Oxalic acid at 1–2 oz/gal and hydrogen peroxide (100% vol) at 0.5 oz/gal mixed in solution with a trace of sulfate will also act as a brightener.

MAGNESIUM ALLOYS

Pickling

Removal of mill scale, corrosion, and heavy oxides may be accomplished in the following solutions:

	Make-up	*Maintenance*
1. Hydrofluoric acid	23% vol	24–29 oz/gal as HF
Temperature		Room

Solution should be water-clear before parts are processed—allow sludge to settle.

	Make-up	*Maintenance*
2. Phosphoric acid	20 oz/gal	16–20 oz/gal
Nitric acid (40° Baumé)	2.5% vol	2–3.5 oz/gal
Ammonium bifluoride	0.25 oz/gal	0.03–0.25 oz/gal

This solution may be used as an electrolytic pickle at 2–6 V.

Control by draw off and replacement when parts are left stained after rinsing in cold water.

Removal of surface contamination and pickling of parts *with minimum dimensional change* may be accomplished in the following solution:

	Make-up	*Maintenance*
3. Chromic acid	48 oz/gal	44–48 oz/gal
Sodium nitrate	4 oz/gal	3.5–4.0 oz/gal
Chlorides		0.01 oz/gal max. as Cl
Sulfate		0.05 oz/gal max. as SO_4
pH		0.7
Temperature		65–90°F
Etch rate		20–30 microin./side/min

Note that chromic acid is used here because replacements are not presently available. Check with commercial suppliers for nonchromate alternatives.

Small quantities of fluorides, chlorides, and sulfates alone or in any combination activate the solution. Increasing the ions increases etch rate and increasing chlorides may cause pitting.

	Make-up	*Maintenance*
4. Ferric sulfate (anhydrous)	13.5 oz/gal	8.5–13.5 oz/gal
Hydrofluoric acid	2.2 fl oz/gal	1.5–2.5 oz/gal of fluoride (total)
Temperature		125–135°F
5. Phosphoric acid (85%)	Full strength	
6. Sodium chloride	4 oz/gal	2.5–4.0 oz/gal
Sulfuric acid (concentrated)	27 oz/gal	17–27 oz/gal
Temperature		160–180°F
7. Phosphoric acid	24 oz/gal	23–35 oz/gal
Ammonium bifluoride	2 oz/gal	0.5–2.0 oz/gal
Temperature		Room to 100°F or 190–212°F

NICKEL AND COBALT ALLOYS

Many of the baths used to pickle stainless steels will also work for these alloys.

The permanganate scale loosening bath given under Iron and Steel, solution 6, can be used to treat parts with heavy scale. A 30-minute soak will loosen the scale so that it can be removed in any of the following baths or the nitric/hydrofluoric baths under Stainless Steels.

For alloys covered by AISI 661, 670, 680, 688:

	Make-up	*Maintenance*
1. Hydrofluoric (70%)	50% vol	48–58 oz/gal
Nitric acid (40° Baumé)	7.5% vol	7–10 oz/gal
Temperature		Room
2. Sodium hydride	1–2% wt	—
Sodium hydroxide	98–99% wt	—
Temperature		680–720°F

Parts treated in the molten bath that develop scale, and pure nickel or Monel parts, may be treated in hydrochloric acid.

	Make-up	*Maintenance*
3. Hydrochloric acid (22° Baumé)	50–75% vol	—
Temperature		Room

Parts with light scales and discoloration can be treated in the following solutions. Nickel silver (German silver) can also be treated in solution 4.

	Make-up	*Maintenance*
4. Sulfuric acid (66° Baumé)	5% vol	10–15 oz/gal
Ferric sulfate (anhydrous)	24 oz/gal	22–24 oz/gal
Temperature		180°F
5. Hydrochloric acid (22° Baumé)	25% vol	10–13 oz/gal
Ferric sulfate (anhydrous)	13 oz/gal	10–13 oz/gal
Temperature		160–180°F

SILVER

Silver and silver alloys can be treated in strong acids and in cyanide solutions typical of the following:

	Make-up	*Maintenance*
1. Nitric acid (40° Baumé)	66% vol	—
Temperature		Room to 160°F
2. Sulfuric acid (66° Baumé) 88% vol —		
Nitric acid (40° Baumé)	22% vol	—
Temperature		Room

Work must be dry when immersing, or spotting will occur.

	Make-up	*Maintenance*
3. Tri- or tetra-sodium ethylene diamine tetra acetic acid	3 oz/gal	2–3 oz/gal
Sodium aluminum sulfate	6 oz/gal	—
or		
Sodium potassium tartrate	6 oz/gal	—
Temperature		120–130°F

Solution is used with 4–6 V cathodic current for very short periods of time (30–60 sec.).

STAINLESS STEELS

Stainless steels can be pickled in a variety of acid solutions including hydrochloric acid. However, because hydrochloric acid can cause intergranular attack and residual chloride ions may cause stress corrosion during service of the part, it is not recommended as a pickle solution.

The scales that form on stainless steels are sometimes resistant to acid treatments and attempts to remove them with acids can cause pitting and etching of the substrate. It is recommended that such scales be loosened in scale conditioning prior to pickling.

Scale Loosening

		Make-up	*Maintenance*
1.	Sodium hydroxide	25 oz/gal	20–25 oz/gal as Na_2O
	Sodium carbonate (anhydrous)	25 oz/gal	
	Potassium permanganate	8 oz/gal	6–8 oz/gal
		Temperature	190°F to boiling
2.	Sodium carbonate (anhydrous)	20 oz/gal	7–9 oz/gal as Na_2O
	Sodium hydroxide	5 oz/gal	
	Potassium permanganate	12 oz/gal	10–12 oz/gal
	Temperature		190°F to boiling
3.	Sodium carbonate (anhydrous)	12 oz/gal	10–12 oz/gal
	Potassium permanganate	12 oz/gal	10–12 oz/gal
	Temperature		190°F to boiling

Pickling

		Make-up	*Maintenance*
4.	Nitric acid (40° Baumé)	30% vol	30–65 oz/gal
	Hydrofluoric acid (70%)	4% vol	To maintain etch rate
	or		
	Ammonium bifluoride	6.7 oz/gal	
	Etch rate		0.001–0.003 in./side/hr
	Dissolved metal		3 oz/gal max. of Fe
	Temperature		120–140°F

Immerse for 5-minute intervals for a total of 30 minutes. Further processing may cause etching.

Many variations of this bath exist with both higher and lower acid concentrations and with wetting agents. Lower fluoride slows etch rate; higher nitric acid allows the bath to function at lower temperatures. Any of these solutions may etch cold-worked areas of parts, so they should be used with caution.

	Make-up	*Maintenance*
5. Sulfuric acid (66° Baumé)	6.25% vol	
Hydrofluoric acid (75%)	6.25% vol	
Molybdic acid	14 oz/gal	
Temperature		To 180°F
6. Ferric sulfate	13 oz/gal	9–13 oz/gal
Hydrofluoric acid (75%)	1.7% vol	1.5–2.5 as fluoride
Temperature		125–135°F
7. Sulfamic acid	10 oz/gal	
Ferric sulfate	0.25 oz/gal	
Temperature		160–180°F
8. Nitric acid (40° Baumé)	40% vol	45–70 oz/gal
Molybdic acid	0.5 oz/gal	0.3–0.5 oz/gal

This solution will remove foreign metals, especially lead, and will leave the part passive.

Passivation

	Make-up	*Maintenance*
9. Nitric acid (40° Baumé)	40% vol	45–70 oz/gal
Temperature		Room to 145°F
10. Nitric acid (40° Baumé)	25% vol	20–35 oz/gal
Molybdic acid	6 oz/gal	2.5–4.0 oz/gal
Temperature		70–150°F

STEEL

See Iron and Steel.

TITANIUM

Solution 4 under Stainless Steels can be used; however, the following bath is preferred because the higher nitric acid content gives better assurance of avoiding hydrogen embrittlement.

	Make-up	*Maintenance*
1. Nitric acid (40° Baumé)	40% vol	40–60 oz/gal
Hydrofluoric acid (75%)	2.4 % vol	To maintain etch rate
or		
Ammonium bifluoride	4 oz/gal	
Dissolved metals		4 oz/gal of Ti
when also used for CRES		3 oz/gal of Fe
Temperature		120–135°F

May be used with a wetting agent to lower surface tension and give better wetting.

	Make-up	*Maintenance*
2. Fused sodium hydroxide	100% wt	—
Temperature		800°F

The permanganate scale looseners, solutions 1 and 2 under Stainless Steels, may be used followed by pickling in solution 1 above.

ZINC AND ZINC ALLOYS

Zinc can be activated by immersion in 1% by volume solutions of sulfuric or hydrochloric acids. For bright finishes, these should be used with chromic acid.

	Make-up	*Maintenance*
Sulfuric acid	20 oz/gal	15–20 oz/gal
Sodium sulfate	4 oz/gal	2–4 oz/gal
Temperature		Room
Time		30–45 sec.

ZIRCONIUM

Zirconium with heavy scale should be treated in a scale conditioning bath, such as the permanganate solutions 1 and 2 under Stainless Steels. This is followed by short immersion in a nitric/hydrofluoric bath such as solution 4 under Stainless Steels or the following:

	Make-up	*Maintenance*
Nitric acid (40° Baumé)	47% vol	50–60 oz/gal
Hydrofluoric acid (75%)	5% vol	2–5 oz/gal
Temperature		Room

Excessive fluorides will etch the metal. If etching occurs, reduce total fluoride.

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PREPARATION OF BASIS METALS FOR PLATING

by Earl C. Groshart

Consultant, Seattle

If a plated deposit is to realize its full value on a part, it is absolutely necessary that it have the best possible adhesion to the part. The part must be scrupulously cleaned to achieve any adhesion, but to achieve maximum adhesion, each basis metal must be treated to a series of steps that remove all traces of foreign materials and leave it active enough to form metallurgical bonds as well as physical ones. The processes given here are intended to do this on a production basis. Where common production solutions can be used, i.e., solutions that can be for more than one metal, they will be specified.

It will be assumed that parts reaching the plating department or shop will have been made ready for plating. All machining, grinding, polishing, straightening, and other mechanical operations should be finished; all heat-treating, thermal aging, and stress relieving should have been accomplished; and all mill scales, rolling scales, or heat treating scales should have been conditioned for easy removal.

Other sections of this *Guidebook* (cleaning, pickling, polishing, etc.) provide complete instructions for accomplishing many of these operations.

PRECLEANING

Precleaning is designed to remove the bulk of the contamination from the part surface in the least expensive way, thus protecting the more expensive and more important final solutions. It is also the step necessary to provide a part that is clean enough for masking and racking.

The first step, which was traditionally done with solvent vapor degreasers, has largely been supplanted by modern solvent/water or alkaline emulsion cleaners because of the environmental and health hazards associated with degreasing solvents. Following cleaning with these emulsions, the parts should be thoroughly rinsed.

Alkaline cleaners devoted to the removal of grease, oil, polishing or drawing compounds, grinding and machining coolants, and general shop dirt will work equally as well as solvents, but should be restricted to those jobs and should not be expected to produce water-break-free surfaces.

Heavy rusts and scales must be removed prior to plating. Pickling, sandblasting, or electrocleaners are used. When electrocleaners are used, it is best that they not be the same solutions used in the general plating lines. Once the bulk of these soils has been removed, the parts should be clean enough to apply any required maskants and to rack.

LOW CARBON STEELS

Cleaning

Thorough cleaning, either in a strong alkaline soak cleaner (pH above 11) or in an anodically operated electrocleaner, is the first step. The cleaners should be free rinsing and suitably compounded as steel cleaners. The preferred electrocleaner should be operated hot (up to 200°F) with a current density of 50–100 A/ft^2 with a voltage source of 6–9 V. Hot soak cleaners may require mild rack or solution movement. Use 1–4 minutes for electrocleaning and up to 30 minutes for soak cleaning.

Rinsing

Rinse preferably in a two-stage rinse in warm (140–150°F) water. A fog spray over the top of the cleaner tank helps to keep the hot solution from drying on the parts before they are rinsed and can be used to replace evaporation losses. Rinse thoroughly; at this stage the parts must have a water-break-free surface, i.e., a surface where water forms a sheet without breaking over unwet areas.

Activating

Without drying, immerse the parts into an acid solution to remove any light oxides, rust, or scale. A 5–10% by weight solution of hydrochloric acid (31%) for 5–15 seconds at room temperature is preferred; however, higher concentrations and temperatures are also usable. A 10% solution of sulfuric acid at room temperature and a 10–20% solution of sulfamic acid are also excellent activator solutions.

Rinse

Follow immediately by another rinse, preferably cold water, which can be followed by a warm water rinse if the parts are going into a warm plating solution and transfer time is short enough so that they will not dry before being immersed in the plating solution.

If plating is not immediate, they may be stored in a solution of 2–4 oz/gal of sodium hydroxide or the alkaline cleaner up to several hours. After removal they should be rinsed, given an acid dip, another rinse, and plate. As an alternative to acid treatment for activation, treat the part in a periodic reverse solution as given under High-Strength Alloy Steels below.

HIGH CARBON STEELS

These steels (over 0.35% carbon) require much the same treatment as low carbon steels, but because they have a tendency to form a smut during the pickling operation, an extra step is required to remove it. Also, because the higher carbon steels are used in the hardened condition and under sustained loads (parts such as springs and lock or bellville washers), they must be treated so that they do not become embrittled during the plating operation.

Stress Relieving

High carbon steel parts, which have been subjected to any cold working operations, except shot peening or polishing, should be stress relieved prior to plating. This can be accomplished by baking at 350–400°F for 0.5–3 hours just prior to the final preparatory plating steps.

Cleaning

Anodically electroclean in free rinsing alkaline solutions using the techniques established for low carbon steels. Soak cleaning is not recommended for racked parts; however, tumbling in a soak cleaner is preferred for bulk parts. Thoroughly rinse.

Oxide Removal

Treat in 10% hydrochloric acid, without inhibitors, for the minimum length of time required to remove the oxides, rust, and scales. Alternatively, a 20% solution of sulfamic acid at 120–140°F for the minimum time can be used.

Smut Removal

Smut, which may have formed, must be removed. Anodic treatment in the electrolytic cleaner can be used, or, if the smut is light, it will be removed in the etch treatment that follows.

Etching

Anodically etch in a sulfuric acid solution (up to 70 oz/gal H_2SO_4) at a temperature below 85°F. The addition of Na_2SO_4 (15–18 oz/gal) will help provide a microetch on the harder, high carbon steels. A current density of 100–400 A/ft^2 for a time not to exceed 2 minutes is sufficient. Thoroughly rinse. The periodic reverse treatment shown for high-strength steels is an effective alternative.

HIGH-STRENGTH ALLOY STEELS

Steels, which have a hardness of Rockwell C 38 or above, are considered high strength and must be treated very carefully to prevent hydrogen embrittlement of the steel.

Stress relieving of these steels just prior to plating is very important as any cold working of the surface just adds to the embrittlement problem. If no specific baking time and temperature are given for the operation, the following general guide can be used.

Stress relieve bake at a temperature 50–75°F below the tempering temperatures (800°F maximum) for the material involved for a time of 3 hours minimum. If the tempering temperature is not known, bake at 350–400°F for 3 hours minimum.

Abrasive Blasting Technique

The most popular procedure uses dry abrasive blasting of the parts after a suitable precleaning for bulk grease, etc. removal and alkaline cleaning. Aluminum oxide, garnet, or other suitable nonmetallic abrasives should be used. Plating should be started within 30 minutes of blasting. A 10–30 second dip in 3–5% hydrochloric acid (followed by a cold water rinse) just prior to plating has been helpful in promoting adhesion, providing a smut is not formed. Smuts can be treated as for high carbon steels when required.

Electrocleaning Technique

After parts have been suitably precleaned, masked, and racked, they can be treated in an electrolytic cleaner using periodic reverse current. There are many commercial solutions that are satisfactory or the following formula is suggested.

Sodium hydroxide, 10–20 oz/gal
Trisodium phosphate, 5–10 oz/gal
Glutamic acid (monosodium glutamate), 4–8 oz/gal
Surfactant, as required to foam smoothly

This should be operated on a periodic reverse: 10 seconds cathodic—10 seconds anodic; always ending on an anodic cycle. The bath can be operated from room temperature to 150°F, the warmer temperature being required to remove heavy scales. Time will range from 2 to 20 minutes, depending on the amount of scale, oxides, etc. to be removed.

This treatment is followed by through rinsing, first in warm water followed by cold water. The part should now be ready to plate. A short dip in a sulfamic acid solution (10–12 oz/gal) at room temperature will enhance adhesion on those steels (1095, H 11), which tend to form a light smut after electrolytic activation treatment.

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Postplating

These steels will require up to 24 hours of baking after plating depending on the plating bath used and the hardness of the steel. The plating procedures should be followed carefully.

STAINLESS STEEL

The plating of stainless steel is complexed by the immediate formation of a passive oxide on the cleaned surface. An adherent plating cannot be applied to this passive film, so a simultaneous activation/plating step is included.

The removal for processing soils, polishing compounds, etc., follows the standard precleaning steps for steel. Because of the poor conductivity of stainless steels, extremely good rack contact should be made. It is also advisable to increase the area of such contacts or to add extra contacts.

Alkaline Cleaning

Both soak cleaners and electrolytic cleaners can be used. For high chromium steels and highly polished steels, the minimum exposure to the high alkalinity and high current density of steel electrocleaners is recommended, as they tend to "frost" a bright finish.

Activation

Cathodic treatment of 5 A/ft^2 in a room temperature solution of 12–40 oz/gal of sulfuric acid (s.g. 1.8) for 1–5 minutes, followed by a quick rinse and immediate nickel plate will be satisfactory for most of the low chromium-nickel alloys and the PH hardenable alloys, but the universal activation treatment is the simultaneous activation/nickel strike procedure, known as the Wood's nickel strike.

The formula for this need not be precise, but a 1:1 ratio of nickel chloride and hydrochloric acid is recommended.

Nickel chloride, 16–64 oz/gal
Hydrochloric acid, 8–32 fl oz/gal
Operate at room temperature using nickel anodes and a current density of 20–200 A/ft^2
Plate, 1–4 minutes

The bath is successfully used by starting work anodically at 10–20 A/ft^2 for 2 minutes, followed by cathodically treating as shown in the formula. Other procedures place the work in the solution and allow it to sit for a few minutes, then plate. Ferrous chloride may be substituted for the nickel chloride when it is necessary to reduce the use of nickel because of EPA and health considerations.

This treatment will leave the stainless steel in an active condition, ready to receive other plating; however, this activity will last only a short while and will be lost if rinsing and plating do not follow immediately.

Rinses should have a pH below 7, but no special requirement other than not contaminating the rinse with alkaline solutions is necessary. Whenever possible, current should be on the parts when they are immersed into the plating bath.

ALUMINUM

The first step in plating aluminum involves an alkaline etch of the surface to remove the surface layer and provide a fine etch. A 1–3 minute immersion in a hot (160–180°F) solution containing 3 oz/gal of sodium carbonate and 3 oz/gal of trisodium phosphate, or a 30–60 second immersion in a 5% solution of sodium hydroxide at 120–140°F will accomplish this.

Acid Treatments

The alkaline etch will expose many of the alloying elements in the various alloys and will probably leave a light smut on the parts. To remove this and provide an active surface, various acid treatments are recommended.

Pure Aluminum and the 3000, 5000 Series

Dip in a 50% solution of nitric acid at room temperature for 30–60 seconds.

2000 and 6000 Series

Etch 1–2 minutes in a hot (180°F), 25% sulfuric acid solution, followed, after a rinse, by a 30–60 second, room temperature, 50% nitric acid solution.

7000 and High Silica Castings

Dip in a solution that is three parts nitric acid and one part hydrofluoric acid, for 30–60 seconds at room temperature.

Zincating

Following these steps, the most popular method of applying plating is to use the zincate method, which applies an immersion coating of zinc on the cleaned part. Some suggested solutions are:

1. Sodium hydroxide, 16 oz/gal
   Zinc oxide, 2.7 oz/gal
   Sodium potassium tartrate, 6.7 oz/gal
   Sodium nitrate, 0.13 oz/gal
   Time, 30 seconds
2. Sodium hydroxide, 67 oz/gal
   Zinc oxide, 13 oz/gal
   Ferric chloride hexahydrate, 0.3 oz/gal
   Sodium potassium tartrate, 1.3 oz/gal
   Time, 30–60 seconds

The double zincate process applies the first zinc coating, followed by an immersion in 50% nitric acid solution to strip the zinc, then the zinc is applied as a second coat. The second coating is much more uniform than the first.

Commercial zincate and commercial bronze solutions are also very successful, as is immersion into a noncyanide zinc plating tank.

Copper Striking

The zinc surface is now plated with copper from a low pH bath. One formula is:

Copper cyanide, 5.6 oz/gal
Sodium cyanide, 6.7 oz/gal
Sodium carbonate, 4.0 oz/gal
Sodium potassium tartrate, 8.0 oz/gal
Free cyanide (by analysis), 0.8–2.0 oz/gal
Temperature, 120–130°F

pH, 10.2–10.5
Current density and time, 25 A/ft^2 for 2 min, then 15 A/ft^2 for 3 min.

An alternative is to apply electroless nickel in place of the copper. This is especially useful if the final coating is to be electroless nickel.

A third alternative for wrought materials is to anodize in a standard chromic acid anodizing bath (10% chromic acid) until the voltage reaches 20 V. Immediately remove, rinse, and apply electroless nickel using an auxiliary anode to start the plating.

Chemically pure (CP) aluminum can be treated in a phosphoric acid anodize bath until the voltage starts to rise, then it can be transferred to a chromium bath for direct chromium plating.

COBALT

Cobalt and its alloys react to plating much as stainless steel and nickel. The oxide that forms, even after scale conditioning treatments, is difficult to remove.

The nickel or ferrous chloride solution shown under Stainless Steel, operated to the following limits, is successful in plating cobalt:

Nickel or ferrous chloride, 60–70 oz/gal
Hydrochloric acid, 30–35 oz/gal

The bath can be operated slightly above room temperature, up to 100°F, as a soak pickle for 5 minutes prior to turning on the anodic current at 100 A/ft^2 for 2–4 minutes to strike plate the part. Transfer through a quick rinse to the plating solution. It is generally a good idea to go into any cyanide or alkaline solution with the current on at low voltage.

Using the sulfuric anodic etch shown under Nickel will remove any heavy scales from cobalt, but the nickel strike should be used. Cobalt chloride, when available, may be used to make up the strike, which can be used with either cobalt or stainless steel anodes.

COPPER AND COPPER ALLOYS

Precleaning

Removal of heavy scales, oxides, drawing lubricants, etc., is covered elsewhere, in the pickling section of this *Guidebook*. Oil, grease, and organic soils can be removed in a standard emulsion cleaner.

Alkaline Cleaning

In general, the cleaners used for steel can be used for copper. Soak cleaners with work rod agitation are satisfactory, although electrolytic cleaning is preferred. Both anodic and cathodic cleaning are satisfactory. Anodic cleaning may cause slight etching of the material, particularly brass, if applied for long periods of time. Cathodic cleaning may cause smutting. Commercial cleaners are recommended, but a basic formula can be used:

Sodium hydroxide, 5–8 oz/gal
Sodium carbonate, 10–15 oz/gal
Trisodium phosphate, 8–15 oz/gal
Wetting agent, 0.1 oz/gal

Temperature, 140–160°F
Current density, 10–30 A/ft^2
Time, 1–3 minutes cathodic; 5–10 minutes anodic

The same solution, with or without the sodium hydroxide, can be used as a cleaner for small parts that can be tumbled.

Activating

Solutions of 5–10% by volume of sulfuric acid or 10–20% by volume of hydrochloric acid are commonly used. The solution should be at room temperature; immersion time should be less than 30 seconds. The same HCl pickle can be used for steel, but close control of the dissolved copper must be observed or it will plate out on the steel, usually as a black powder. Parts to be plated in a fluoborate bath can be dipped in 8–10% by volume fluoboric acid solution, then transferred to the plating bath without rinsing.

Leaded copper will require dipping in a solution containing nitric acid, as the lead will not dissolve in the other acids. A solution containing 10–20% by volume nitric acid and 2–5% by volume fluoboric acid is satisfactory. When "bright dipping" is used, the parts may go directly through the rinse to the plating bath.

Beryllium copper forms hard-to-remove scales during heat treating operations. Solutions 1 and 4 under Copper Alloys, found elsewhere, in the pickling section of this *Guidebook*, will remove these scales and leave the beryllium copper in an active condition.

Striking

A copper strike is recommended for the brass alloys, the beryllium alloys, and the alloys containing lead or containing soft solder (such as at joining seams). A nickel strike or thin nickel underplate is also desirable for plating nickel, chromium, or gold and is necessary for rhodium and platinum.

Silver requires its own strike, even when copper and nickel have been used. See the individual metal sections elsewhere in this *Guidebook* for solution chemistry and operating conditions.

LEAD

Lead and its alloys can be successfully plated by cleaning in a periodic reverse alkaline cleaner, ending on the anodic cycle. Any standard electrocleaner is satisfactory.

Activation

1. Treat for 15–30 seconds in a 10% fluoboric acid solution to which 3–6 fl oz/gal of 30% hydrogen peroxide have been added. Rinse and plate.
2. Anodic etch in 4–10% fluoboric acid solution for 5–15 seconds at 6 V. Rinse and plate.

MAGNESIUM

Magnesium is a difficult-to-plate metal with many varied alloys and several forms, adding to the complexity of plating. For a successful production operation, it appears that the process should be tailored to the alloy and form; however, the following general process will work for most alloys.

Cleaning

Soak in a caustic solution with the pH maintained at 12 or above. Steel soak cleaners with extra caustic work satisfactorily.

Pickling

The following pickles are recommended:

For AZ31B Alloys

Chromic acid, 45–50 oz/gal
Nitric acid, 2–3 oz/gal
Hydrofluoric acid, 0.5–0.8 oz/gal
Room temperature for 1–5 minutes

For Other Alloys

Phosphoric acid, 180–200 oz/gal (130 minimum)
Room temperature with mild agitation for 1–5 minute immersion.

Activator

Following pickling, parts are activated in the following solution. This forms a fluoride coating on the surface to prevent oxidation.

Phosphoric acid, 32–38 oz/gal
Ammonium bifluoride, 7–9 oz/gal fluorine

Zincate

The fluoride will dissolve in the following bath and be replaced with a blue-gray coating of zinc.

Zinc sulfate, 1–1.6 oz/gal as Zn
Tetra sodium pyrophosphate, 10–12 oz/gal as pyrophosphate
or
Tetra potassium pyrophosphate, 10–12 oz/gal as pyrophosphate
Temperature, 140–180°F for AZ31B; 160–190°F for others
Mild agitation
Immersion time to form a uniform blue-gray coating, 1–5 minutes

Copper Strike

The zinc surface is now copper plated in the following:

Potassium cyanide, 9.0 oz/gal (0.5–1.5 as CN)
Cuprous cyanide, 5.5 oz/gal (3.6–3.9 as Cu)
Potassium fluoride, 4 oz/gal (1.0–1.3 as F)
pH, 9.6–10.4
Temperature, 130–140°F

The bath should be mildly agitated and operated with twice the anode area as part area to prevent polarization. Parts should go into the bath with the voltage set at 1–2 V and then be adjusted quickly to prevent gassing.

A Rochelle copper strike has also been used effectively. The copper-plated parts can now be plated with whatever metal is required.

The noncyanide alkaline coppers, which are replacing many cyanide coppers, have been shown to work satisfactorily, but testing before starting a production facility is recommended.

MOLYBDENUM

Molybdenum is plated to protect it from catastrophic oxidation when used at very high temperatures.

Alkaline Clean

Any electrocleaner will be satisfactory. Soak cleaners used for steel are also satisfactory.

Activation

Anodic etch in the following solution:

Sulfuric acid, 118 oz/gal
Phosphoric acid, 96 oz/gal
Current density, 70–80 A/ft^2
Time, 2–3 minutes
Room temperature

Treatment is followed by etching in the following solution:

Potassium ferricyanide, 40 oz/gal
Potassium hydroxide, 13 oz/gal
Current density, 100 A/ft^2
Time, 1–1.5 minutes
Temperature, 185°F

Strike immediately in a standard high chromium bath containing 67 oz/gal CrO_3 and 0.67 oz/gal H_2SO_4. This can be followed by plating in a chloride nickel bath.

NICKEL

Nickel and high nickel alloys react like stainless steels and can be treated in the same simultaneous activation-nickel striking baths.

Anodic etch in 25% sulfuric acid at 20 A/ft^2 for 10 minutes, followed by 200 A/ft^2 for 2 minutes, and then treat cathodically for 2–3 minutes at 200 A/ft^2. This will allow for heavy deposits and simultaneous addition of steel for electroforms.

SILVER

Silver and its alloys are very corrosion resistant to atmospheric oxygen, but are susceptible to tarnish by atmospheric sulfides and nitrates, so they will have a dark to black appearing tarnish or scale as they emerge from manufacturing and polishing operations. Polishing compounds are removed in the usual way with alkaline cleaners and solvents (see Precleaning).

Electrolytic cleaning (2–4 V for 1–2 minutes) in a solution of sodium hydroxide of 5–10 oz/gal at room temperature will remove this tarnish. To aid in quick removal, the same solution can be used warm at 100–120°F. This is followed by a rinse before moving on.

Immersion in a 10% solution of 30% by volume hydrogen peroxide will remove silver tarnish and leave the surface platable.

TITANIUM

This metal is difficult to plate and with most known methods, a thermal treatment, which bonds the plate to the titanium, is necessary to get satisfactory adhesion. Various alloys react differently and require tailored processes as shown.

Cleaning

The standard methods of providing a water-break-free surface are satisfactory for titanium. Chemically pure (CP) titanium, 6A1–4V and 4A1–4Mn, may be treated:

	Make-up	*Maintenance*
Pickle:		
Nitric acid	50 oz/gal	40–50 oz/gal
Ammonium bifluoride	35 oz/gal	25–35 oz/gal
Wetting agent (linear alkylated sulfonic acid)	0.04 oz/gal	
Room temperature		
Rinse in cold water		
Etch:		
Nitric acid	50 oz/gal	40–50 oz/gal
Hydrofluoric acid	0.25 oz/gal	0.1–0.25 oz/gal
Wetting agent (linear alkylated sulfonic acid)	0.04 oz/gal	
Temperature, 180–210°F		
Time, 20 minutes		

This is followed by plating chromium, copper from an acid bath, or nickel.

Following the final plate thickness, the part is baked in an inert atmosphere (argon) for 1–5 hours at 800–1,200°F.

CP titanium, 3A1–5Cr, 5A1–2Cr–2 Mo, 6A1–V, can be treated as follows:

Blast clean all alloys with a liquid slurry of pumice, aluminum oxide, or glass beads. Grit size can be from 100 to 1,250 or any of the pumice flours, but should only be used for titanium. Immediately after blasting, the parts should be nickel or electroless nickel plated. For small areas, brush plating is satisfactory. Adhesion with this method is very good. Baking may not be required, especially with brush-plated nickel.

TUNGSTEN

Remove gross contamination by mechanical means, sandblasting followed by alkaline soak cleaning in a hot alkaline cleaner.

Anodic etch in the following solution to remove surface metal.

Sodium hydroxide, 0.5–2.0 oz/gal
Temperature, 135–145°F
Current density, 150–225 A/ft^2
Time, to remove required metal and scale

To remove light scales, anodic etch in 10% sulfuric acid at room temperature at 50 A/ft^2.

Activate

1. Treat in a 20–40% solution of hydrofluoric acid at room temperature, using 4–6 V AC. Use either two parts in the solution or a platinum electrode as the second part. Plate immediately in an acid electroplating bath.

2. Treat by anodically etching in a 4 oz/gal potassium hydroxide solution, 120–140°F, for 2–3 minutes. Rinse and then neutralize in a 10% sulfuric acid solution. Strike immediately in a chromium bath, 33 oz/gal, 100:1 ratio. This is followed by immersion in a 20% hydrochloric acid solution for 2–5 seconds, rinse, and then nickel sulfate strike. The desired metal can now be plated onto the part.

ZINC- AND ZINC ALLOY-BASED DIE CASTINGS

Zinc castings usually require a number of mechanical operations to smooth the parting lines and the rough cast surfaces, and to repair defective surfaces. This operation may leave greases and buffing compounds burned, caked, and ground into the parts. It is advisable to remove these as soon as possible to prevent etching of the metal, which can occur if compounds are left for long periods in a moist environment.

Precleaning

Alkaline emulsifiers can be used with brushes to remove the heavy buffing compounds. Solvent emulsion cleaning may also need some mechanical assistance in removing buffing compounds. Spray emulsion cleaning is effective.

Cleaning

Anodic electrocleaning is recommended. The cleaner solutions should be made up with mixed alkalies, trisodium phosphate, metasilicate, etc., and should contain no (or not more than 0.1 oz/gal) sodium hydroxide. Current densities should be 15–30 A/ft^2 and the time should be limited to 30–45 seconds for solutions operated at 180°F. Longer times may be required if the solutions operate at lower temperatures. Rinsing is extremely important. A warm rinse followed by a cold rinse, followed by a second cold rinse, are the minimum required.

Acid Activating

A 25–45 second dip in a 0.25–0.50% sulfuric acid solution at room temperature should remove smut and zinc oxides, which tend to form in the alkaline cleaners. Again, thorough rinsing is required. All traces of acid should be removed from porous areas and other surface irregularities or the parts will blister at these spots after plating.

Copper Striking

A standard copper strike can be used. At least 0.04 mil should be applied to castings, which will be further copper plated and 0.1–0.12 mil when nickel plate is used.

ELECTROPLATING SOLUTIONS

BRASS AND BRONZE PLATING

by Henry Strow

Oxyphen Products, Oakville, Conn.

Brass plating is one of the oldest cyanide plating solutions. Records of it go back to 1841 in Russia by a German chemist. All of the alloys, from pure copper to pure zinc, can be plated and useful alloys cover most of the entire range. Much of the literature is incomplete and contains false conclusions. The range of solutions that can be used is extremely wide, so only some of the most useful and stable are given.

The uses of brass plate are largely decorative, with thin plates (flash plates) over bright nickel or other bright plates predominating. Heavier plates can be buffed or burnished to a bright smooth finish or can be treated to produce antique finishes usually brown or black. These finishes can be relieved by brushing or tumbling to produce highlights.

Although decorative finishes predominate, engineering uses are also important. Brass plating can be used on zincated aluminum prior to nickel plating. A very important use is for rubber bonding. The greatest use is in the plating of steel tire cord wire, where the bond of the rubber to the steel depends on brass plating the steel wire. The brass plating is done on heavier wire, which can be drawn after plating to the final size without destroying the integrity to the brass plate. The usual analysis of the brass is 65–68% copper.

A wide variety of formulations can be used. The cyanide complexes of copper and zinc are so stable and of the right order that the copper and zinc deposition potentials are very close. All of the useful brass plating solutions are based on cyanide. Noncyanide brass plating is possible and has been used commercially, but with limited success. Noteworthy are the pyrophosphate-based solutions and solutions based on hydroxylaliphatic acid salts. Because of the stable cyanide complexes, the ratio of copper to zinc in the solutions has no relationship to the plated alloy.

There are three basic types of solutions used. First is the conventional low temperature (70–100°F), with a wide range of compositions and alloys plated. Second is a similar solution operated at a temperature above 110°F. Third is a solution with a hydroxide content above 1 oz/gal and usually with higher metal content.

The conventional solution has a wide range of compositions, depending on use. The following composition is typical and may be varied widely, subject to certain rules.

Copper cyanide	4.2 oz/gal (32 g/L)
Zinc cyanide	1.3 oz/gal (10 g/L)
Sodium cyanide	6.5 oz/gal (50 g/L)
Sodium bicarbonate	1.5 oz/gal (10 g/L)
Sodium carbonate	2.5 oz/gal (18 g/L)
Ammonia	0.25–1 gal/100 gal

This gives an analysis as follows:

Copper (as metal)	3.0 oz/gal (22 g/L)
Zinc (as metal)	0.7 oz/gal (5 g/L)
Sodium cyanide (use analysis as for total sodium cyanide in cyanide zinc solutions)	3.0 oz/gal (22 g/L)
pH	10.2–10.4
Temperature of operation	75–95°F (25–35°C)

Zinc oxide may be used instead of zinc cyanide, but it must be lead free and preferably French (USP) process. Since the zinc oxide generates hydroxide, the carbonate used should be all bicarbonate to keep the pH down.

This solution is a general purpose solution. For barrel plating, the concentration should be higher for added efficiency. The concentration should be two-thirds the listed concentration for still tank plating and one-third for flash plating. The weaker solutions give more uniform plating thickness and better uniformity color in deep recesses.

The efficiency of plating is governed by three factors. The first is copper content with the efficiency increasing with copper content. The second is cyanide content with the efficiency decreasing as the cyanide to zinc ratio rises above 3:1. The higher cyanide decreases the throw in deep recesses. The normal ratio of cyanide to zinc is three up to five for yellow brass. Efficiency increases with temperature especially with dilute solutions.

Ammonia controls the plating alloy. Adding ammonia increases the zinc content in the plating alloy. With no ammonia, a red-colored brass is produced. A large excess of ammonia can produce white, banded deposits. An increase in temperature eliminates this. Ammonia also brightens the deposit.

Carbonate in large amounts is an impurity, but about 4 oz/gal is essential to stabilize the plating. Carbonate in low pH solutions exists as an equilibrium of carbonate and bicarbonate known as sesquicarbonate.

The pH may vary from 9.8 to 10.8 without adverse effect. To raise the pH, add sodium hydroxide. Lower pH solutions may release cyanide in ventilation air so the pH should normally be kept above 10.3.

Addition agents generally do not improve the plating from a solution in proper balance, but may be useful in extending the plating range. Wetting or foaming agents may be useful in suppressing fumes, but must be chosen carefully since many wetting agents used in cleaners and other solutions may cause organic contamination and brown plate.

Under normal conditions it is not necessary to add ammonia to the solution if the temperature of operation is 90°F or less. If the solution is not operated for more than a few days, an addition may be necessary. Air agitation also strips ammonia from the solution.

A second type of solution uses the same basic formula as the first, but at the higher concentrations and at temperatures of 140°F and higher. Since ammonia is fugitive at these temperatures, addition agents to replace the ammonia are necessary. Ethylene diamine, propylene diamine, and monoethanolamine or mixtures thereof and similar amine compounds are recommended at concentrations of 0.25–1% by volume. These materials are stable at higher temperatures and require only small additions to maintain color.

A third, entirely different, type of brass plating solution was developed by DuPont in 1938. It involves the use of sodium hydroxide to complex the zinc and higher concentrations of copper. It gives high plating efficiency. A typical formulation is as follows:

Copper cyanide	10 oz/gal (75 g/L)
Zinc cyanide	3 oz/gal (22 g/L)
Sodium cyanide	17 oz/gal (125 g/L)
Sodium hydroxide	6 oz/gal (45 g/L)

This will give an analysis of:

Copper (as metal)	7 oz/gal (50 g/L)
Zinc (as metal)	2 oz/gal (15 g/L)
Total sodium cyanide	8 oz/gal (60 g/L)
Sodium hydroxide	6 oz/gal (45 g/L)
Temperature of operation	140–160°F

Addition agents are necessary to give uniform color and throw in recesses. Higher temperatures can give higher speeds especially for wire and strip plating. The solution may also use potassium salts for higher efficiency and may also be diluted for flash plating.

Impurities are a problem in all brass plating solutions. The most widely encountered impurity is lead. Amounts as little as 10 ppm can cause redness in recesses. The cause is most often lead in the anodes. All the metals in the tank and even the stamping lubricants on the work being plated should be suspect. Tin in larger amounts in the anodes will cause color problems. Both lead and tin should be less than 0.1%. Iron is seldom a problem, but if it is in the anode circuit it may dissolve, forming ferrocyanides, which combine with zinc, forming insoluble zinc ferrocyanide and clouding the solution. Zinc ferrocyanides are filtered out either by batch filtration or continuous filtration.

The normal analysis of brass anodes for yellow brass plating is 70% copper/30% zinc. The normal analysis of yellow brass plate is about 75% copper/25% zinc. This gives a slight excess of zinc in the anodes and makes for a more stable solution. For red brass plating, 85–15 or 90–10 anodes should be used, depending on alloy being plated.

Organic impurities, which include soaps and some wetting agents, may cause brown deposits. Carbon filtration either batch or continuous will eliminate this.

Anodes may be cast, rolled, or extruded with good results for all types. Anode baskets should be of titanium to eliminate iron contamination.

Equipment for brass plating may be of any conventional type. Barrels may be of conventional design as well as still tanks and strip or wire machines. Tanks should be lined or of plastic construction to avoid stray currents and iron contamination.

Solutions may be used to plate alloys with higher copper content, such as 85–15 (rich low brass) or 90–10 (architectural bronze), by slightly modifying the standard solution, using higher copper content, lowering the zinc content, and increasing the cyanide content to give a ratio of total sodium cyanide to zinc from 7 to 9 times the zinc metal content. Ammonia is necessary but kept very low.

A typical formula is as follows:

Copper cyanide	6 oz/gal (45 g/L)
Zinc cyanide	1 oz/gal (7.5 g/L)
Sodium cyanide	10 oz/gal (75 g/L)
Sodium bicarbonate	1 oz/gal (7.5 g/L)
Sodium carbonate	1 oz/gal (7.5 g/L)
Ammonia	0.5–1 pint/100 gal (60–120 ml/100 L)
Temperature	80–110°F

Control of this solution is more critical since the alloy must be held within 1% to maintain color. The ratio of cyanide to zinc is the major controlling factor in color. Excess ammonia will give a yellow color or two-toned plate. The pH is the same as in yellow brass and is not a major factor in color.

WHITE BRASS

Alloys of brass with more than 50% zinc are white. They are also brittle limiting them to thin deposits to avoid cracking. The deposits with addition agents are fully bright and may be directly chromium plated. They have been used as an intermediate layer under nickel and chromium plate to secure better corrosion resistance. They have been used on articles such as shopping carts. These coatings are not often used today, with their major uses back in the 1950s.

Several formulations are used to secure varying zinc contents. A typical formulation is as follows:

Copper cyanide	2.3 oz/gal (17 g/L)
Zinc cyanide	8.5 oz/gal (64 g/L)
Sodium cyanide	11.5 oz/gal (85 g/L)
Sodium hydroxide	8.0 oz/gal (60 g/L)
Current density	10 to 40 A/ft^2
Alloy composition	75% zinc/25% copper

Anodes are usually balls or chunks since bars tend to crack. Composition of the plate with this formulation is about 28% copper. Alloy composition may be varied by varying cyanide and hydroxide content. Raising the amounts increases the zinc content.

BRONZE PLATING

Copper-tin alloys are used for decorative fittings, for corrosion protection of builders' hardware, and for bearing surfaces. Alloys with 10–12% tin have a golden color, which can closely resemble gold and is sometimes used for costume jewelry.

A typical formulation is as follows:

Sodium cyanide	8.6 oz/gal (64 g/L)
Copper cyanide	4.0 oz/gal (30 g/L)
Sodium stannate	4.6 oz/gal (35 g/L)
Sodium hydroxide	1.5 oz/gal (10 g/L)
Rochelle salt	6.0 oz/gal (45 g/L) (or equivalent)
Temperature	160°F (70°C)

Anodes are usually pure copper. Addition of tin as stannate is necessary to maintain the tin content. Use of bronze anodes will produce a black color in the solution and result in poor performance.

Addition agents improve the range and can produce a bright plate by the use of a small amount of lead. Since copper forms only a cyanide complex, and tin forms only an alkaline complex, control is simple by varying metal content and controlling the cyanide and hydroxide content.

A variation of the bronze solution, which produces a plate that is about 40% tin, has a pewterlike finish. This alloy is known as speculum.

A typical formulation is as follows:

Sodium cyanide	5 oz/gal (37 g/L)
Copper cyanide	2.7 oz/gal (20 g/L)
Sodium stannate	7.5 oz/gal (100 g/L)
Sodium hydroxide	11.5 oz/gal (10 g/L)
Rochelle salts	5 oz/gal (38 g/L)
Temperature	160° F (70° C)

Operation of this solution is very similar to the standard bronze solution. Control of the alloy depends on analysis of the deposit since the color does not vary with minor changes in analysis. Fairly frequent addition of stannate salts is necessary due to the large tin content of the deposit.

CADMIUM ELECTROPLATING

by Hugh Morrow

International Cadmium Association, Great Falls, Va.

Traditionally, most cadmium electroplating has been carried out in alkaline cyanide baths prepared by dissolving cadmium oxide (CdO) in a sodium cyanide solution. In recent years, environmental concerns and regulations have shifted the emphasis away from the alkaline cyanide processes toward the acid sulfate or neutral chloride systems, which are prepared, respectively, with either sulfuric acid or ammonium/potassium chloride solutions. Acid fluoborate systems have also been employed to plate cadmium, but their utilization has generally been more widespread in Europe than in the United States.

ALKALINE CYANIDE BATHS

The operating characteristics of an alkaline cyanide cadmium plating bath are determined by the ratio of the total sodium cyanide (NaCN) to cadmium metal content. Sodium hydroxide (NaOH) and sodium carbonate (Na_2CO_3) are formed by reactions in the bath and additional NaOH may be added to improve conductivity and counteract solution drag-in. The compositions of several typical alkaline cyanide cadmium plating baths are summarized in Table I.

The choice of a plating bath depends on the size and configuration of the workpiece being plated. Large numbers of small parts are most conveniently barrel plated with solutions of a lower NaCN to Cd ratio, whereas larger parts with intricate or recessed surfaces must be coated by still plating techniques of high throwing power to obtain complete coverage. Automatic plating lines are often used for intermediate-sized products, which are arranged on racks and then sequenced through a series of plating procedures.

Cadmium balls suspended in steel wire cages serve as the plating anodes, and excess anode area must be provided for the steel cages. All cadmium electroplating baths employ proprietary addition agents to impart a uniform, fine-grained deposit, and to ensure bright cadmium coatings, but excessive amounts of these addition agents are discouraged. Other factors that are normally specified for cadmium plating baths include the current density and temperature, which, along with the bath composition, will affect plating efficiency, plating speed, deposit uniformity, and hydrogen evolution tendency.

Preparation of the Plating Bath

Bath preparation is most conveniently carried out in a spare tank of approximately the same volume as the production plating tank. Fill the tank roughly 70% full of water, heat to

Table I. Alkaline Cyanide Cadmium Plating Baths

	Concentration (oz/gal)				
Total NaCN to Cd Ratio	*Cd*	*CdO*	*NaCN*	*NaOH*	*Na_2CO_3*
4.0	2.6	3.0	10.4	1.9	4–10
4.1	2.6	3.0	10.7	8.0	4–6
4.5	4.8	5.5	21.6	3.4	4–6
5.0	2.7	3.0	13.5	1.9	4–8
7.2	2.6	3.0	18.2	1.9	4–6

90°F, and dissolve the sodium cyanide. For barrel plating, 1.0 oz/gal of sodium hydroxide may be added at this time to improve solution conductivity. Carefully add the CdO while continuously stirring the solution to ensure that the CdO dissolves completely.

After all salts have been dissolved, add 1.5–2.0 pounds of purification grade zinc dust per 100 gallons of solution and stir thoroughly for 30 minutes. Let the solution stand for four hours, then filter it into the production plating tank, leaving about 5% of the solution along with sediment at the bottom of the plating bath make-up tank.

Install approximately one cadmium anode per linear foot of conductor bar, and electrolyze at 0.25–0.50 V for 24–48 hours. Add the grain refining agent as required, and plate for about 2 days at a current density of 10 A/ft^2 to normalize the solution.

Production Plating Conditions

Still Plating

A cathode current density of 5–70 A/ft^2 may be used, but the normal ranges are 15–25 A/ft^2 for nonagitated baths and 30–50 A/ft^2 for agitated baths. The maximum anode current density should be about 20 A/ft^2. Bath temperature should be 75–90°F, but should preferably be held at 80–85°F. The cadmium metal content will be established by the plating process required (e.g., high throwing power or high speed/high efficiency). The free cyanide content is normally 8–10 oz/gal, but a higher level is necessary at higher temperatures to ensure uniform coatings. The sodium carbonate concentration should be limited to 8 oz/gal or to even lower values for baths with high metal content. The combination of high cadmium metal content and high sodium carbonate content tends to polarize the anodes, limit the usable current density range, and produce dark and streaky deposits.

Barrel Plating

Small barrels may be operated at 6–8 V. For barrels larger than 14 in. in diameter by 30 in. in length, the voltage should be increased to 10–12 V. The NaCN to Cd ratio for barrel plating is generally at the low end of the range, and normally at low current densities, 5–7 A/ft^2, depending on the metal concentration and bath temperature.

ACID SULFATE BATHS

Acid sulfate baths are the most popular of the noncyanide cadmium plating processes. This process produces bright deposits by both rack and barrel plating techniques with good throwing power, plating speed, and efficiency. Various additives are utilized in the acid sulfate cadmium plating baths to maintain the bright deposition characteristics of the bath, extend the bright plating range, replenish drag-out losses, and assure a fine-grained deposit.

Preparation of the Plating Bath

The sequence of bath preparation for the acid sulfate cadmium plating solutions is similar to that for the alkaline cyanide baths. Fill a tank 50–70% with water. One supplier recommends adding cadmium next in the form of cadmium oxide, whereas another prefers adding sulfuric acid first followed by cadmium oxide. In either case, care must be taken to completely dissolve the cadmium salts and with the handling of sulfuric acid. Brighteners, grain refiners, and other additives are then added as recommended by the specific supplier. The solution compositions as recommended by the two suppliers of acid sulfate cadmium plating baths are summarized in Table II.

Table II. Make-Up Compositions of Acid Sulfate Baths

	Amount per 100 Gallons Solution	
Component	*Supplier 1*	*Supplier 2*
Cadmium oxide	37.5 lb	18.8 lb
Sulfuric acid (s.g. 1.84)	96.0 lb	62.0 lb
Brighteners	2–7%	2–3%
Grain refiners	1%	1.5–2.5%
Other additives	0.8%	0.1%

Table III. Operating Conditions for Acid Sulfate Plating Baths

	Concentration or Operating Range	
Component or Condition	*Supplier 1*	*Supplier 2*
Cadmium	4–6 oz/gal	2–4 oz/gal
Sulfuric acid (free)	8–12 oz/gal	6–12 oz/gal
Brightener	1 gal/10,000 A-hr	2–3%
Grain refiner	Not specified	1.5–2.5%
Temperature	60–90°F	67–73°F
Cathode Current Density	10–30 A/ft^2	10–20 A/ft^2 (barrel) 30–75 A/ft^2 (rack)
Anode Current Density	Not specified	15–50 A/ft^2

Production Plating Conditions

Acid sulfate cadmium plating baths generate heat during operation and should be cooled to produce consistently good results. Tanks should be lined with polyvinyl chloride (PVC), polyethylene, polypropylene, rubber, or other materials with equivalent corrosion resistance to sulfuric acid. Slab or cast high-purity cadmium anodes should be used, and cast carbon can be utilized in place of some cadmium anodes to regulate the cadmium anode surface area, and thus the cadmium concentration, in the bath. Agitation by either cathode rod movement or solution movement is generally recommended for rack plating, but is not necessary for barrel plating operations provided that the perforation size of the barrels is sufficient. The ball anodes are normally suspended in coated or plastic anode containers, with spiral zirconium wire or ribbon contacts and titanium anode hooks. The production plating conditions recommended by the two suppliers of acid sulfate cadmium plating solutions are summarized in Table III.

NEUTRAL CHLORIDE BATHS

A neutral pH chloride cadmium plating bath has also been developed, which is reported to possess excellent throwing power and produce bright cadmium coatings with very high corrosion resistance. When this process was originally developed, it was reported that maintaining the stability of the solution was very difficult. Since that time, stabilizing systems have been developed by the supplier, which allow use under a wide range of operating conditions. The obvious advantage to a neutral chloride cadmium plating system is the absence of cyanides and strongly corrosive acids, both of which necessitate special handling precautions and procedures. This process is suitable for both rack and barrel plating, and requires no cooling.

Preparation of the Plating Bath

A polypropylene or a PVC tank, or a tank with similar acid corrosion resistance, should be utilized for the preparation of the plating solution. The lined tank should first be leached

Table IV. Operating Conditions for Neutral Chloride Plating Baths

	Concentration or Operating Range	
Component or Condition	*Optimum*	*Range*
Cadmium	2.0 oz/gal	1.5–2.8 oz/gal
Ammonium/Potassium chloride	32 oz/gal	30–36 oz/gal
Brightener stabilizer	12 oz/gal	10–14 oz/gal
Solution stabilizer	8% (vol.)	7–8% (vol.)
Proprietary brightener	5% (vol.)	4–6% (vol.)
True brightener	0.3% (vol.)	0.1–0.5% (vol.)
pH	7.2	7.0–7.8
Temperature	80°F	70–100°F
Agitation	Good mechanical agitation	
Cathode current density		10–80 A/ft^2
Anode current density		10–20 A/ft^2

with a 5% hydrochloric acid solution for 12–24 hours, and then rinsed with clean water until the pH rises above 5.0. Fill the tank approximately 70% with hot water and add cadmium chloride to a level of 8% by volume. A proprietary mixture of ammonium and potassium chloride is next added to concentrations of 30–36 oz/gal and is mixed well to dissolve all salts. A proprietary brightener stabilizer is added in amounts of 12 oz/gal followed by addition of 8% by volume of a proprietary solution stabilizer. The pH of the solution should then be checked and should be maintained below a level of 7.5. Add 5% by volume of the proprietary brightener and mix well. Install cadmium and carbon anodes as required, bring the volume of the production tank to its final working level with hot or cold water, depending on the temperature, and measure the pH and adjust to 7.2 with dilute hydrochloric acid or ammonium hydroxide as required. Finally, add 0.3% of the proprietary true brightener and mix well.

Production Plating Conditions

Both mechanical agitation and filtration are required for the neutral chloride cadmium plating process. Because the stability of the bath is critical, it is important to add the proprietary solution stabilizer for any additional cadmium chloride make-up material, which is added due to cadmium metal depletion. The proprietary brighteners are utilized mainly to maintain color, brightness, and leveling of the deposit, and should be replenished at periodic intervals as follows:

Proprietary brightener: 1 gal/10,000–20,000 A-hr
Proprietary true brightener: 1 gal/20,000 A-hr

The solution stabilizer is the most critical element of the bath and should be checked on a per-shift basis. As the process is a neutral to slightly alkaline one, sufficient levels of stabilizer must be maintained to prevent formation of white, insoluble cadmium hydroxide. The solution stabilizer also helps to maintain the color and brightness of the coating and prevents rough deposits. Finally, the pH range must be maintained in the neutral to slightly alkaline range by hydrochloric acid or ammonium hydroxide additions to prevent dull deposits on the acidic side or excessive use of stabilizer on the alkaline side. The operating conditions and concentration ranges for the neutral sulfate cadmium plating process are summarized in Table IV.

ACID FLUOBORATE BATHS

Acid fluoborate baths have been utilized more extensively in Europe than in the United States to plate cadmium, and have been known for some time; however, they have not been

Table V. Operating Conditions for Acid Fluoborate Baths

Component or Condition	*Concentration or Operating Range*
Cadmium	12.6 oz/gal
Cadmium fluoborate	32.2 oz/gal
Ammonium fluoborate	8.0 oz/gal
Boric acid	3.1 oz/gal
Licorice	0.1 oz/gal
Temperature	70–100°F
Current density	30–60 A/ft^2

used to any great extent because they are expensive and equally as toxic as cyanide solutions. Because of the higher solubility of cadmium in fluoboric acid, compared with sodium cyanide, solutions with much higher cadmium metal content can be utilized, resulting in higher cathode efficiency, faster plating rates, and lower hydrogen embrittlement. These are used mainly for barrel plating operations, but are characterized by poor throwing power compared with other cadmium plating processes. Little commercial information is available on establishing and operating acid fluoborate cadmium plating baths, but the bath constituents and operating conditions found in the literature are summarized in Table V.

DECORATIVE CHROMIUM PLATING

by Donald L. Snyder

Atotech USA Inc., Rock Hill, SC

Electrodeposition of decorative chromium is the principal means of imparting the physical and chemical properties of chromium to the surface of less expensive and easier-to-form materials such as steel and plastics. The most desirable properties of chromium as a metal coating are its inherent protective and decorative characteristics. The deposit's high reflectivity is retained in service because of chromium's excellent tarnish, corrosion, wear, and scratch resistance.

Decorative chromium is almost exclusively plated over a nickel electrodeposit, which can easily be plated over substrates such as plastics, steel, aluminum, copper alloys, and zinc die castings. Nickel is preferred because it protects the substrate from corrosion, helps give chromium a white color, and is protected from surface oxidation by the chromium. Stainless steel is the only substrate that is frequently plated directly with chromium, but a nickel preplate before chromium is also used. Multiple or single layers of nickel and copper can precede the nickel/chromium deposits depending upon the intended use of the part. Decorative chromium deposits typically are plated in the 2–20-millionths-of-an-inch range. Thicker deposits tend to be duller and contain visible cracks.

The traditional chromium deposit is produced from an electroplating electrolyte containing hexavalent chromium ions and has a pleasing bluish white decorative appearance. About 1975, a chromium electrolyte containing the less toxic and less hazardous trivalent chromium ion began replacing many decorative hexavalent chromium electroplating installations. Depending upon the process, trivalent chromium electrolytes can either produce a metallic white deposit almost identical in appearance to the bluish white hexavalent chromium deposits, or a deep-looking pewter or stainless steel appearing deposit. In almost all chromium plating applications, both hexavalent and trivalent chromium deposits are interchangeable with each other; however, one or the other process might offer unique advantages. Fluoride will etch substrates, such as steel, resulting in iron contamination of the plating bath.

CHEMISTRY FOR HEXAVALENT CHROMIUM

Hexavalent chromium electrolytes require a source of chromium and one or more catalysts in order to plate. The formulation of the traditional process, called the conventional bath, contains hexavalent chromium and sulfate as the only catalyst. Proprietary additives can be added to the conventional hexavalent chromium plating bath formulation to enhance particular plating operations or the deposit's properties. In most cases, these proprietary processes are called mixed-catalyst baths since the additives contain at least one additional catalyst in addition to sulfate. Fluorides are most commonly used as the second catalyst.

Mixed-catalyst baths are used when their special properties are required, but they are more expensive to operate than are conventional processes. They typically plate at faster speeds, have better coverage, have wider bright ranges, and are more tolerant to impurities. They are also less sensitive to current interruptions and can be plated over more passive surfaces.

The basic formulations of both types of hexavalent chromium processes are very similar. They consist of chromic trioxide (CrO_3), which when combined with water forms chromic acid (H_2CrO_4), and the sulfate ion (SO_4) added in the form of sulfuric acid or a sulfate salt. Even though chemically incorrect, in most plating literature solid chromic trioxide is commonly referred to as its hydrated form, chromic acid.

A number of sometimes conflicting theories have been proposed to explain the very complex mechanism of hexavalent chromium electroplating. Basically, they all resemble the following multiple reactions that are presented in a simplified form.

$$CrO_3 + H_2O \rightarrow H_2CrO_4 \rightarrow CrO_4^{-2} + 2H^+ \qquad (1)$$

$$2H_2CrO_4 \rightarrow H_2Cr_2O_7 + H_2O \rightarrow Cr_2O_7^{-2} + 2H^+ + H_2O \qquad (2)$$

Deposition reaction:

$$Cr_2O_7^{-2} + 14H^+ + 12(e)\text{—CAT} \rightarrow 2Cr^0 + 7H_2O \qquad (3)$$

CAT is a required catalyst, e.g., sulfate and/or fluoride, while (e) refers to an electron. The plating efficiency of reaction (3) is $<\sim 20\%$ depending upon the catalyst and the current density.

Side reactions:

$$2H^+ + 2(e) \rightarrow H_2(\text{gas}) + \text{mist } (H_2SO_4 + Cr^{+6} + H_2O) \qquad (4)$$

This reaction consumes $\geq 80\%$ of the available power. The mist can be trapped within the tank by the use of mist controls or surface tension reducers.

$$Cr_2O_7^{-2} + 14H^+ + 6(e) \rightarrow 2Cr^{+3} + 7H_2O \qquad (5)$$

$$2Cr^{+3} + 3O_2 - 6(e) \xrightarrow{PbO2} 2CrO_3 \qquad (6)$$

Reaction (6) is catalyzed by the PbO_2 film on the lead anode.

Dilute conventional formulations consist of ~250 g/L (33 oz/gal) chromic trioxide ("chromic acid"), with ~2.5 g/L (0.33 oz/gal) sulfate. Concentrated conventional baths contain ~400 g/L (53 oz/gal) chromic trioxide and 4.0 g/L (0.53 oz/gal) sulfate. In practice, however, concentrations in between these are used.

The dilute formulation is extensively used to give good coverage, moderate nickel substrate activation, and consistent current efficiency. It also has a lower cost to originally make up, plates faster, and produces less waste to treat. The concentrated formulation gives better coverage and greater resistance to impurities and requires lower operating voltages; however, it is more expensive to operate because of its higher chromium concentration and the resulting additional chromium to be waste treated.

A critical point in all bath formulations is the requirement for close control of the CrO_3/SO_4 weight ratio needed to produce consistent plating results. Ratios of between 80:1 and 130:1 are typical, with a ratio of ~100:1 being most common for conventional processes. A low ratio results in relatively poor throwing and covering power and an increased limiting current density. Higher ratios result in slow deposition rates, produce dull deposits, have increased covering power, and decreased limiting current density.

The addition of a fluoride catalyst necessitates an adjustment in the CrO_3/SO_4 weight ratio. Ratios of 170:1 to 210:1 are required, with 190:1 being most typical. The chromium concentrations for both the dilute and concentrated mixed-catalyst formulations are the same as for conventional baths; however, the sulfate concentration is lowered.

Unlike most plating baths in which the metal, M, is present in solution as a cation, M^+, the chromium metal is present as an anion complex, $Cr_2O_7^{-2}$, which very likely undergoes further complexing with ions such as the sulfate catalyst to permit chromium deposition. Fluoride or silicofluoride ions are extensively used today in mixed-catalyst formulations, especially in proprietary self-regulating baths. The solubility constants of sparingly soluble salts of the catalysts are utilized to control the catalysts' ratio in self-regulating baths because only enough catalyst will dissolve. For this reason, less frequent catalyst analysis is required. Much more routine analyses and chemical control of the catalysts are needed in non-self-regulated formulations since they must be added to the bath as they are depleted.

Chromic acid concentrations may be maintained by making frequent specific gravity determinations using a hydrometer. Occasionally, more accurate chromium analyses should be conducted by an analytical method specific for chromium. Chromium is consumed and dragged out of the bath. It is replenished by additions of chromic acid since lead anodes are used.

Sulfate concentrations should be determined frequently by measuring the volume of the sulfate precipitated with barium. Occasionally, gravimetric analyses should be conducted to confirm the quick, less accurate, centrifuge method. Sulfate concentrations may be raised by adding sulfuric acid. To add 0.05 g/L sulfate (SO_4), add 0.0295 ml/L concentrated (66° Bé) H_2SO_4. Sulfate is both dragged into and out of the tank. To lower the concentration of sulfate by 0.05 g/L of H_2SO_4, add 0.01 g/L barium carbonate. Sulfate is an impurity in other chemicals such as chromic acid. For this reason, sulfate should be controlled carefully and any sulfate present as impurities should be accounted for.

CHEMISTRY FOR TRIVALENT CHROMIUM

Decorative trivalent chromium, a safer and more efficient system, was developed in the mid 1970s to eliminate some of the problems associated with hexavalent chromium chemistry: high toxicity, low current efficiency, poor metal distribution, lack of coverage around holes, burns in high-current-density areas, and "white-wash." The literature contains far less information on the chemistry of trivalent chromium processes than for hexavalent. This is the result of the relative newness of the commercially successful processes, the proprietorships of the processes, and the wider differences in the chemistries used. Basically, the significant reactions in the trivalent chromium processes are very simple.

Deposition reaction:

$$Cr^{+3} + 3(e) \rightarrow Cr^0 \tag{7}$$

Side reaction:

$$Cr^{+3} \rightarrow Cr^{+6} + 3(e) \tag{8}$$

Reaction (8) can take place at the anode under some conditions.

The electrolytes for trivalent chromium plating solutions differ in chemistry, but they all contain a source of trivalent chromium, which is typically added as the sulfate or chloride salt. They also contain a stabilizing material that combines with the chromium to permit it to plate in the desired form. Salts are also added to increase conductivity in the solution. Wetting agents are used to help in the deposition reaction and to reduce the surface tension of the solution. This reduced surface tension essentially eliminates the formation of a mist at the anode or cathode.

Historically, the method used to eliminate the side reaction (8) distinguished the single-cell from the double-cell process. The original single-cell process has built into the bath chemistry and anodes a mechanism to stop this reaction from occurring. A secondary mechanism converts hexavalent to trivalent if any does appear in the solution. Normal addition of additives to the bath is all that is necessary to eliminate hexavalent chromium. The anodes are placed below solution level to eliminate misting.

The double-cell process stops the side reaction by isolating the chromium-containing solution from the anode by putting each lead alloy anode into a box with its own chromium-free electrolyte. Because of maintenance problems and the space the anode boxes took from the plating area inside the tank, they have been almost completely replaced, over the last few years, by insoluble metallic catalytic composite anodes with a projected life of 3 to 5 years.

Once through the learning curve, control of trivalent chromium plating processes is typically easier than for hexavalent chromium processes. The literature says that an operator should "think nickel plating not chromium plating" when controlling a trivalent chromium process. The troubleshooting guides for trivalent chromium processes are a few lines long compared with several pages for hexavalent chromium. The additives are added based upon

Table I. Chromium Plating Typical Operating Conditions

	Trivalent Chromium	*Hexavalent Chromium*
Chromium, g/L		
Single cell	4–25	100–300
Double cell	4–15	
pH	2.0–4.0	<1
Temperature, °F	70–120	9–120
Cathode current density, A/ft^2	40–150	175–300
Agitation	Mild air	Optional
Rectifier voltage	4–15	4–12
Anode–cathode ratio	2:1	1:1–3:1
Anode material		
Single cell	Carbon	Lead-7% tin
Double cell	Lead-7% tin	
Maximum thickness, mil		
Single cell		
Room temperature	~0.05	≥5
High temperature	≥1	
Double cell	~0.01	
Plating rate, mil per min		
Single cell (constant)		
Room temperature	0.004–0.007	0.004–0.007
High temperature	0.007–0.010	
Double cell (average)	≤0.004	

amp-hours, specific gravity, and pH. In addition, chemical analysis on a monthly basis appears to be sufficient for control. At least one of the graphite-anode single-cell process uses a resin to remove all common metallic contaminates directly from the working trivalent chromium solution. This eliminates the problems attributed to metallic contamination. All trivalent chromium processes are far more sensitive to metallic contamination than hexavalant processes. Metallic impurities darken the deposit and alter the throwing and covering powers.

OPERATIONS

The typical operating conditions for trivalent and hexavalent chromium electroplating processes are shown in Table I.

EQUIPMENT

Tank linings for both types of processes must be made from suitable synthetic material such as PVC or plastisol. Hexavalent chromium uses lead-7% tin anodes, which are consumed during plating. Heating and cooling coils for hexavalent chromium processes can be made from the same lead alloy or synthetic materials.

The single-cell trivalent process uses graphite insoluble anodes that only need to be replaced when mechanically damaged. The double-cell process uses consumable lead anodes with the anode boxes or insoluble anodes with a recoatable catalytic coating without the anode boxes. Titanium or Teflon spaghetti coils are used for heating and cooling in both trivalent processes.

In most cases, a plating line adequately designed for one process can be used for another after thorough cleaning. For trivalent chromium processes, lead and hexavalent chromium

Table II. Trivalent and Hexavalent Chromium Comparison

	Trivalent Chromium	*Hexavalent Chromium*
Throwing power	Good	Poor
Covering power	Good	Poor
Current interruptions	Completely tolerant	Intolerant
Rectifier ripple	Completely tolerant	Intolerant
Deposit structure (microdiscontinuous)		
Single cell	Microporous and microcracked	Special processes required
Double cell	Microporous and microcracked	
Ease of burning	Very hard	Easy
Ease of rinsing	Easy	Moderate
Color buffing requirement	Never	Occasional
Filtering requirement		
Single cell	Only after chemical purification	Never
Double cell	Daily with carbon	
Conditioning/dummying		
Single cell	Never	Start up each day
Double cell	Start up and routinely	
Passivity of nonplated surfaces	Needs postdip	"Chromate" surfaces
Color of deposit		
Single cell		
Ambient temperature	Pewter or stainless steel	Blue-white
Elevated temperature	Metallic white	
Double cell		
Elevated temperature	Metallic white	
Waste treatment	Easy	Moderate
Relative safety	Similar to nickel	Similar to cyanide
Misting	Almost eliminated	Heavy
Odor	Almost eliminated	Strong and dangerous
Removal of impurities	Easy	Hard

must be completely removed since they both act as poisons. For hexavalent chromium processes, small amounts of trivalent chromium act as a poison.

The current carrying capacity of the plating racks must be designed for the highest amperage they will carry. They must also be designed so that the parts on the racks will utilize the bath's plating benefits and minimize the bath's negative plating characteristics. The plating amps for hexavalent chromium processes are at least twice those used for trivalent processes so the racks must be heavier to carry the current. In general, racks designed for hexavalent chromium processes can be used in trivalent processes, but the reverse is not true.

Since trivalent chromium processes will not "burn" and they have greater covering and throwing powers than hexavalent processes (see Table II), the parts can be placed closer together on the racks and high current density areas can face the anodes. This increases productivity and makes shielding and robbing of the part's high current density areas, as is required for hexavalent chromium processes, unnecessary. Auxiliary anodes are sometimes necessary with hexavalent processes to obtain coverage in the recesses, but typically unnecessary in trivalent processes.

Trivalent chromium processes do not require scrubbers and, if the room is adequately ventilated, tank ventilation is typically not used. This is due to the almost complete elimination of misting and odor with trivalent chromium processes due to a built-in mist suppressor, the low chromium concentration, and the greatly reduced toxicity and oxidizing properties of trivalent as compared with those of hexavalent of chromium. Trivalent chromium solution drains and rinses easily, thus greatly reducing the amount of chromium drag-out. If any solution does dry on the part, it is less hazardous since the chromium is in the trivalent state. It also does not stain the part.

SOLUTION MAINTENANCE

The best waste treatment method is to minimize the amount of solution dragged out of the plating tank. Secondly, return as much dragged-out material as possible back to the tank. Any plating solution that cannot be recovered must be waste treated. Even though this reduces plating solution waste, reduced drag-out keeps contaminants in the plating solution complicating the requirement to maintain a pure enough plating solution to obtain the required deposit properties.

Due to hexavalent chromium's poor draining characteristics and its misting, a large amount of solution is unavoidably removed from a decorative chromium plating tank. Vacuum evaporators and ion exchange are examples of methods used to return dragged-out hexavalent chromium back to the plating tank to save chemical and waste treatment expenses; however, due to the difficulty of removing metallic impurities from hexavalent chromium plating solutions, it is common to send a solution containing an excess of metallic impurities out for recovery.

Trivalent chromium is much more sensitive to metallic impurities than hexavalent chromium; however, the chemistry of most trivalent chromium processes makes it easy to remove metallic impurities thus eliminating the need to ever discard it for normal metallic contamination. Atmospheric evaporators are extensively used to return all the trivalent chromium that can be captured back to its plating tank. In most trivalent chromium processes, metallic impurities can be removed quickly by chemical precipitation or slowly by dummying. The most effective way for at least one trivalent process is to use a resin treatment directly on the plating solution to remove all common metallic impurities. This eliminates the buildup of metallic impurities and excludes any change in deposit color or properties associated with metallic impurities. If a trivalent chromium plating solution has to be waste treated its cost is approximately one-tenth that of treating hexavalent chromium.

Hexavalent chromium processes are essentially insensitive to organic contamination since the hexavalent chromium ion destroys most organics. In the process trivalent chromium ions are formed. Trivalent chromium is also formed at the anodes. Being a contaminant, trivalent chromium must be reconverted back to hexavalent chromium. The most common way is to dummy at a high cathode current density (e.g., anode current density of 12 A/ft^2, cathode current density of 600 A/ft^2). Trivalent chromium processes are also relatively insensitive to organic impurities but sometimes organics must be removed. Occasional carbon filtering is sufficient for some processes while routine carbon/peroxide treatments are needed for others.

CORROSION PROTECTION

Decorative chromium deposits play an important role in the base metal protection provided by nickel/chromium systems. They offer hardness, appealing color, tarnish resistance, wear resistance, and corrosion resistance. Even though decorative trivalent and hexavalent chromium deposits are used interchangeably, there are some important differences.

When corrosion resistance is important, most specifications encourage or require microdiscontinuous chromium deposits. With a controlled pattern of microscopic pores or cracks the corrosion potential between the chromium and underlying nickel deposits is spread out over thousands of corrosion sites. This reduces the anodic current on the nickel at any one site greatly reducing the individual corrosion rate. This results in a fine pattern of active corrosion sites uniformly spaced over the surface. A typical standard will specify a minimum

Table III. Decorative Black Chromium Formulations

	Bath A	*Bath B*	*Bath C*
Chromic acid, g/L	250	340	250
Fluosilicic acid, g/L	—	0.34	0.25
Acetic acid, g/L	216	—	—
Barium acetate, g/L	7.6	11	—
Temperature, °F	100	70	90
Current density, A/ft^2	40–90	200	150–450

of 10,000 micropores per square centimeter or over 30 microcracks per millimeter. Without microdiscontinuity all the corrosion potential would be centered in a few sites resulting in unsightly, irregularly spaced, large corrosion sites.

All trivalent chromium deposits are microdiscontinuous as plated. Deposits under about 20 millionths are microporous. Deposits over about 25 millionth are microcracked. Hexavalent chromium deposits must undergo special treatments to produce microdiscontinuity. Chromium plated over very fine inert particles that are codeposited in a nickel strike over the bright nickel deposit is the typical way of producing microporous chromium. Lightly spraying the hard, brittle chromium deposit with hard 60 to 80 mesh particles produces microporous chromium at the contact points.

If microdiscontinuity is not induced, hexavalent chromium will typically macrocrack (visible to unaided eye) in service if plated over 20 millionth in thickness. Most chromium specifications requiring corrosion protection specify between 10 to 12 millionths of chromium. "Crack-free" hexavalent chromium deposits will typically macrocrack in service since, like all chromium deposits, they are hard and brittle. Specifications used in North America have essentially eliminated microcracked deposits from use. Microcracked deposits tend to lose their reflective appearance much faster than microporous deposits.

Trivalent chromium solutions do not impact short-term corrosion protection by "chromating" the unplated sections of a part as hexavalent chromium ions do. Postchromium plating corrosion inhibiting treatments must be used to obtain an equivalent to this protection.

DECORATIVE BLACK CHROMIUM

Thin black chromium deposits are used for functional and decorative applications. Important functional applications include solar energy collectors for heat production and anti-glare surfaces. Decorative functions include furniture, plumbing fixtures, optical equipment, boat equipment, and builders' hardware. The decorative jet black finish enhances users' appeal for the product and so its popularity depends upon the customers' changing desire for black finishes.

Except for a decrease in wear resistance, black chromium deposits offer a surface with properties similar to that of regular chromium deposits. In addition, black chromium deposits

Table IV. Hexavalent Chromium Barrel Formulations

	Bath A	*Bath B*
Chromic acid, g/L	525	340
Sulfate, g/L	1	0.98
Fluosilicate, g/L	7	6
Temperature, °F	90–105	Room–95
Voltage	6–18	6–18
Time of plating (minutes to produce 10 millionths)	8	10

have a greater degree of microporosity, which helps absorb oil and paint. This property improves its corrosion resistance, wearability, and appearance.

Most black chromium processes are proprietary because of the difficulty of obtaining consistent plating characteristics and deposit properties. In many applications, plating black chromium over regular chromium is recommended. For all decorative and most functional black chromium deposits, the typical thickness is ~10 millionths of an inch. Three general formulations are given in Table III. Low carbon steel anodes can be used with plating times of up to 10 min. Most formulations will only produce a maximum deposit thickness and then stop plating due to the nonconductive nature of the deposit. To produce black deposits, barium salts are typically added to remove any traces of sulfate. Hexavalent chromium formulations are more common but trivalent chromium formulations are available.

BULK CHROMIUM PLATING

Plating racks are typically used to hold parts, transfer parts to and from the plating solution, and to carry the direct current to the part. Very small parts such as eyelets, screws, nuts, and bolts have high labor costs when placed individually on racks so they are sometimes bulk plated in barrels or trays; however, even under the best of plating conditions, the chromium reject rate can be very high. This is due to incomplete coverage and black/gray deposits mostly resulting from poor cathode contact and current interruption.

Both hexavalent and trivalent chromium processes can be used for bulk plating of parts. Hexavalent chromium has been used primarily and special proprietary formulations have been developed that can produce near 100% coverage if precise control is used. Table IV contains typical barrel hexavalent chromium formulations. Since current interruptions are not avoidable in barrels and trays, stalk complexed-fluoride-containing solutions are normally used.

It is extremely important that the bright nickel used prior to chromium not be passive. This is typically accomplished by plating a minimum of 0.1 mil of nickel in the same barrel and, with a few rinses in between, transferring the parts directly into the chromium tank. Since the parts are not held by a rack, poor or no contact with cathode leads is common. Contact must depend upon gravity, while being dampened by the solution, to hold the part against the cathode contact points.

To increase the likelihood of good contact sod satisfactory plating, platers use low current density, low temperatures, and specially designed barrels and trays. Cathode contact points in barrels are constructed from wire mesh, solid steel liners, button contact points less than an inch apart, or steel bars that tumble the parts as they move. Large barrels with small loads also help to increase the frequency of contact and reduce temperature buildup inside the confined space of the barrel. In general, the highest practical current density possible, without burning, should be used.

Screw and spiral design plating equipment are also used. The parts are put into the barrel at one end and transferred through the barrel for plating inside the threads of the screw. This permits a continuous flow of plated parts. Vibratory agitation and centrifugal force barrels are also available. In all cases, the barrels must be constructed so that the hydrogen gas generated during plating can escape from the barrel rather than being trapped and possibly exploding. Tray plating requires that parts be layered onto a metallic screen and vibrated or tumbled during plating.

Trivalent chromium solutions have recently been used for barrel and tray plating of chromium. Since current interruptions do not hurt the deposit in trivalent chromium processes, and burning is never a problem, this technology will probably be much more popular in the future.

FUNCTIONAL CHROMIUM PLATING

by Kenneth R. Newby

Atotech USA Inc., Rock Hill, S.C.

Functional or hard chromium plating is produced from chromic acid solutions, which contain one or more catalytic anions. The chromium metal electrodeposited is extremely hard and corrosion resistant. It has a low coefficient of friction and imparts exceptional wear characteristics to parts on which it is plated. This process is generally used to give deposit thicknesses of >0.1 mil (2.5 μm) and up to 20 mils (500 μm) or more. The major uses are to provide coatings with superior wear, abrasion, and/or corrosion resistance. Functional chromium is also used to rebuild or salvage worn parts such as rolls and roll journals, molding dies, and other tools, cylinder liners, crankshafts, and mismachined items.

CHEMISTRY

The same hexavalent chromic acid solution could be used for both decorative and functional chromium plating; however, to achieve the best possible results in either of these applications, *differing chemistries and operating conditions should be employed.* Those best utilized in decorative applications, where nickel activation and superior chromium coverage are of paramount importance, are described elsewhere. (See separate article on Decorative Chromium Plating). For functional plating, where plating speed and deposit characteristics such as hardness, corrosion, and wear are needed, the chemistries and techniques described below are appropriate.

For functional chromium plating three basic formulations are used. All three use chromium trioxide (CrO_3) as the chromium source. When this chemical is dissolved in water chromic acid (H_2CrO_4) is formed. (Frequently, although technically incorrect, CrO_3 is referred to as chromic acid.) Sulfate ion (SO_4^{2-}) is a necessary catalyst in all chromium plating solutions. It is usually introduced as sulfuric acid or, for small experimental baths, as a salt such as sodium sulfate. In the conventional chemistry, which was developed in the 1920s, these two species are the only constituents.

In the conventional chemistry chromic acid can be present in concentrations of 20 to 60 oz/gal; however, it is most commonly approximately 30 to 33 oz/gal. The sulfate concentration is critical and is always held in a ratio relative to the chromic acid concentration. A CrO_3:SO_4 ratio of 100:1 by weight is most common. At lower ratios, such as 80:1, smoother deposits are obtained, but both the throwing power and the covering power are reduced. At ratios of up to 130:1, the opposite characteristics are found. At even higher ratios dull deposits and slower plating rates are obtained. Several proprietary baths are available that automatically control the chromic acid to sulfate ratio.

The fluoride or mixed catalyst plating baths were commercialized in the 1950s. In these chemistries a higher plating efficiency, typically 20 to 23% (versus 7–15% for conventional), and a harder, more corrosion and wear-resistant deposit is obtained. In this chemistry chromic acid may range from 20 to 50 oz/gal with 28 to 33 oz/gal being the most common. The chromic acid to sulfate ratio is normally in the 150 to 250:1 by weight range. The fluoride is commonly added as the SiF_6^{2-} ion in an amount of 0.25 to 0.4 oz/gal (2–3 g/L). This chemistry provides better substrate activation for plating on bright nickel or nickel bearing alloys such as 300 series stainless steel or Inconel and is less susceptible to problems with current breaks than is the conventional chemistry.

A major limitation of the fluoride or SiF_6^{2-}-containing chemistries, which is not found in the nonfluoride baths, is that exposed steel areas will be chemically etched by the bath while the part is warming up to the plating bath temperature. Also, those low current density areas that are exposed but not plated will continue to be etched during the entire plating cycle. This contributes greatly to the iron contamination of the bath, which ultimately limits its life.

The third type of functional chromium plating chemistry is a nonfluoride high-speed chemistry introduced in 1986. Deposits from this chemistry provide the best wear and corrosion properties available in chromium plating. The operating conditions for this proprietary bath, which

Table I. Examples of Chromium Plating Solutions

Chemical	*Conventional (oz/gal)*	*Mixed Catalyst (oz/gal)*	*Fluoride-Free Proprietary (oz/gal)*
CrO_3	33.0	32.0	33.0
SO_4^{2-}	0.33	0.16	0.33
SiF_6^{2-}	—	0.3	—
Proprietary catalyst	—	—	yes

can be customized for the type of work being plated, generally are 33 oz/gal chromic acid, 0.33 oz/gal sulfate, 130 to 140°F, and an efficiency of 20 to 26%. There is a proprietary secondary catalyst in this chemistry. The chromic acid and secondary catalyst levels are maintained by proprietary addition agents. This bath, being fluoride free, will not attack exposed nonplated steel.

It is possible to convert conventional baths to either mixed catalyst or the high-speed nonfluoride. While more difficult, the mixed catalyst baths can also be converted to the nonfluoride chemistry. Neither of the high-speed chemistries can be easily converted back to the conventional bath.

Table I summarizes the recommended chemistries of each of these three systems in ounces per gallon.

BASIC REACTIONS

The detailed reaction mechanism for the reduction of hexavalent chromium-to-chromium metal has not yet been fully understood. For the plater, however, there are three general reactions that need to be considered. As the cell voltage is increased the first reaction to occur is hexavalent chromium being reduced to trivalent chromium. This is followed by the reduction of hydrogen ions to hydrogen gas and then by the deposition of chromium metal. The reactions in a simplified form can be represented as follows:

$$Cr^{6+} \rightarrow Cr^{3} \quad (1)$$

$$2H^{+} \rightarrow H_2 \quad (2)$$

$$Cr^{6+} \rightarrow Cr_0 \quad (3)$$

A general estimate is that about 10% of the plating current is consumed in the first reaction, which is the generation of trivalent chromium. The amount of current going to the evolution of hydrogen gas is dependent upon the type of chromium plating chemistry being utilized. With the more efficient cocatalyzed baths there is less hydrogen.

At the anode, assuming it to be a lead alloy, the first reaction is the oxidation of the anode surface to a chocolate-brown lead dioxide. On this surface there are two reactions that occur during plating. The predominant reaction is the generation of oxygen. The second is the reoxidation of trivalent chromium back to hexavalent chromium ions. The rate of this reaction is largely determined by the mass transport of the trivalent ion to the anode surface. The reactions can be represented again in a simplified form as follows:

$$Pb_0 \rightarrow PbO_2 \quad (4)$$

$$2H_2O \rightarrow O_2 + 4H^{+} \quad (5)$$

$$Cr^{3+} \rightarrow Cr^{6+} \quad (6)$$

OPERATING CONDITIONS

Typical operating conditions for functional chromium plating are given in Table II.

At higher temperatures smoother deposits with less burning or nodulation will be obtained. Frequently either shields or thieves must be used to prevent severe buildup in the


Thermo-Cote

Table II. Operating Conditions

	Conventional	*Mixed Catalyst*	*Fluoride-Free Proprietary*
Temperature, °F	120–140	130–140	130–140
Cathode current density, A/in^2	0.25–2.5	1–4	1–6
Solution agitation	Optional	Optional	Optional
Anode–cathode ratio	1:1–3:1	1:1–3:1	1:1–3:1
Anode material	Lead-tin (7%) alloy or lead-antimony (6%)	Lead-tin (7%) alloy	Lead-tin (7%) alloy or lead-antimony (6%)

high current density regions. The use of conforming anodes that are shaped so that the anode-to-cathode distances are the same at all points on a part is an excellent method for obtaining a uniform deposit thickness.

Defects in hard chromium plating usually fall into either adhesion or deposit roughness classes. While a detailed treatment of either of those subjects is beyond this article, both problems have frequent causes. Adhesion failures are usually caused by poor cleaning or by an inadequate reverse chromic acid etch for nonnickel- or nonchromium-bearing substrates. In the case of nickel care must be taken to keep the substrate cathodic in order to prevent passivation. In plating chromium onto chromium the part is first made anodic (1 A/in^2 for approximately 1–2 min) and then, to initiate plating, the voltage must be slowly over several minutes ramped up from the lowest rectifier setting possible.

The second type of general defect is that of rough or pitted deposits. If the plating bath chemistry is properly adjusted and the defects are over the entire substrate then the most likely cause is one of poor base metal preparation. A second cause would be improper etching prior to plating. Chromium deposition at best will mirror the substrate and, most frequently, will magnify any pits, scratches, or nodules present on the substrate. If roughness is only in the high current density regions then the use of shields and/or thieves may solve the problem. Also, if throwing power is not of concern the chromic acid-to-sulfate ratio can be lowered to 80 to 90:1. The other alternative is to lower the overall current density.

Plating cathode current efficiencies and plating speeds are given in Tables III and IV.

POWER SUPPLY

Chromium plating differs from other plating systems in that the DC current must be freer of "current breaks" or "current ripple." This is especially important at the low output end where ripple can lead to poor adhesion for chromium being deposited onto chromium. The various types of rectifiers have undergone changes over the years, so it is necessary to choose one that is specifically for chromium plating as compared with zinc, copper, or nickel, where ripple has little importance.

A general rule is that AC ripple should be less than 10% under load, preferably less than 5%, and that no negative spikes (as observed on an oscilloscope, for instance) are produced over the voltage and current range to be used in plating. Occasionally, one phase may go out.

Table III. Cathode Current Efficiency (in Percent)

	Conventional Bath		*High-Speed Baths*[a]	
Current Density (A/in^2)	*130°F*	*140°F*	*130°F*	*140°F*
1.0	10.9	10.8	15.0	14.2
1.5	12.4	12.0	18.5	17.9
2.0	14.0	13.6	21.4	20.6
3.0	16.3	14.9	24.0	23.4
4.0	18.1	17.0	26.0	25.3
5.0	19.4	18.2	26.8	26.2
6.0	20.7	19.3	27.5	27.0

[a] Mixed catalyst or fluoride-free.

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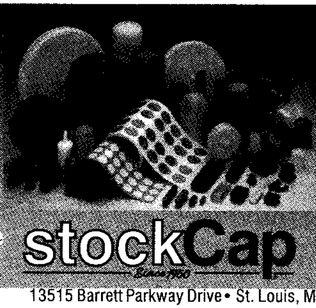

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Table IV. Plating Speeds (in Thousandths of an Inch per Hour)

	Conventional Bath		*High-Speed Baths*[a]	
Current Density (A/in²)	*130°F*	*140°F*	*130°F*	*140°F*
1.0	0.30	0.30	0.42	0.39
1.5	0.52	0.50	0.77	0.75
2.0	0.78	0.76	1.2	1.1
3.0	1.4	1.2	2.0	1.9
4.0	2.0	1.9	2.9	2.8
5.0	2.7	2.5	3.7	3.6
6.0	3.5	3.2	4.6	4.5

[a] Mixed catalyst or fluoride-free.

While in other plating baths this may not produce defective work in chromium plating a dull and frequently rough plate would be obtained immediately, along with a reduction in thickness. Such deposits will have poor corrosion and wear properties. The mixed catalyst baths are less sensitive to AC ripple problems than are the conventional sulfate baths.

ANODES

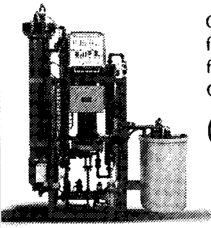
In chromium plating an insoluble anode is used since chromium is replenished by the addition of chromic acid. Iron anodes have been used but are not generally suitable because they add iron to the bath and allow the buildup of trivalent chromium. Platinum or platinized titanium have had limited success. These anodes allow for constant shape and very close anode-to-cathode spacing; however, trivalent chromium is poorly if at all oxidized on these anodes.The universally used material is a lead alloy, especially 7% tin, or 6% antimony, or a combination of both, which oxidizes the trivalent back to hexavalent chromium during electrolysis.

These alloying materials provide corrosion resistance and physical stiffness to the lead anode. Tin provides corrosion resistance and must be present in at least 3% by weight for anodes used in the fluoride mixed-catalyst baths. Antimony, which is usually less costly than tin, provides stiffness to the anode. This minimizes bending or shape changes, which occur over time. A common choice, which incorporates the benefits of both, is an anode composition of 93% lead, 4% tin, and 3% antimony. Anodes typically last from six months to several years. Longer life is achieved in the fluoride-free plating baths.

The reaction at the anode is dominated by the formation and release of oxygen, but a side reaction is the oxidation of trivalent chromium when it is present. During nonplating periods, yellow lead chromate forms on the surface of the lead. Anodes occasionally may be cleaned by electrolyzing outside the plating tank or by soaking in proprietary cleaning solutions. Usually the anodes can be activated by electrolysis before each use. The important thing to watch is that the resistance on the anodes does not rise as they age due to scale buildup.

The ability of the lead anode to keep the trivalent chromium at approximately 0.5 oz/gal or less is dependent on keeping the lead anode (brown, black color) and the ratio of anode to cathode area above 1:1 and preferably above 1.5:1. As the ratio is lowered to less than 1:1 the tendency for trivalent chromium to accumulate in the bath increases sharply. If the amount rises above about 1 oz/gal, problems may become significant. Above 2 oz/gal the problems get progressively worse due to the increasing solution resistivity until the bath becomes unsatisfactory for use. These problems include burning or rough chromium deposits at high current densities, possibly a brown film at low densities, and a tremendous decrease in bath conductivity so that only low currents are obtained at full tank voltages.

If the type of plating requires that the lead anode area be less than the cathode area then auxiliary electrolysis may be required to reoxidize the trivalent chromium. This may be done in the same tank if time (e.g., overnight) or space is available, or it may be done in a separate tank. The anode area may be 20 to 30× the cathode area (e.g., a small cathode with regular tank anodes evenly spaced) to increase the rate of oxidation. Solution agitation is also beneficial.

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Care and control of anodes are as important as control of solution chemistry and operating conditions for successful chromium plating.

FIXTURING AND RACK DESIGN

For both decorative and functional chromium plating careful attention is required for fixturing and rack design. The techniques for decorative plating, with its very thin deposit, are very different than those for functional plating, with its much thicker deposit. In functional chromium (hard chrome) a major objective is to obtain very nearly the same chromium thickness over significant areas of a part. To engineer racks and fixtures the designer must consider:

1. Current distribution, i.e., to obtain complete coverage, prevent high current density burning, and obtain as uniform a chromium thickness as possible over the part.
2. Solution flow, i.e., be sure that all plated areas are supplied with sufficient solution of uniform concentration to prevent corners or recessed areas from depleting the chromium from solution.
3. Parts positioning, i.e., to ensure recessed areas do not form traps for gas bubbles that prevent coverage in that area and "cupping" of solution does not occur, which results in excessive drag-in of impurities into the plating bath and drag-out of chromic acid.

In the choice of racking methods the following must be considered:

1. Number of identical parts to be plated per unit time.
2. Function of the chromium, thickness, area to be plated, and engineering application.
3. Capabilities of the shop to perform finishing operations on the part.
4. Tolerances that must be met by the plater.
5. Shielding or masking areas that are not to be chromium plated.

The racks are usually coated with plastic, which is electrically nonconductive and resistant to chromic acid.

STOP OFFS

Many applications require that specified areas of a part not be plated. These are covered with resists or "stop offs" to prevent local plating. A number of available stop off materials are described in the following section.

Tapes

There are two classes of tapes. First, there are conductive tapes, which accept plated metal and prevent excessive buildup where plating is undesirable. These are made of lead, aluminum, or copper surfaces bonded to an adhesive material. The tapes are quite flexible and can be cut and trimmed with a razor blade; however, during long periods in the tank, the adhesive may fail and lifting of tape at edges may occur. This results in spillover of plating under the tape. Also, the combination of tape adhesive, chromic acid, time, and temperature seems to result in a tenacious residue left on the part when the tape is removed. In many cases, however, lead tape is the most convenient and satisfactory method of stopping off.

A second type of tape used is nonconductive. There are many tapes available in combinations of plastics and adhesives. Some tapes, such as those made of polyesters (e.g., Mylar), are rigid, while some polyvinyl chloride (PVC)-based tapes are stretchable and can be made to conform to the shape of the part.

Conductive tapes are used where one wants to plate the surface being masked in order to obtain more uniform chromium thickness on the area actually being plated. The tape acts as a current robber. Insulating tapes are usually less expensive than conductive tapes. Also, there are as many occasions where one wants to insulate an adjoining nonplated surface as there are for plating such a surface. For example, when plating an outside diameter up to a shoulder one wants to insulate the shoulder.

Lacquers

There are a number of chromic acid-resistant lacquers available. They can be applied by spraying, dipping, or painting. They are an insulating material, the same as nonconducting tape. The chief advantage of lacquer stop offs is the selective way in which they can be painted or sprayed were needed.

Table V. Solar Properties for Several Surface Materials

Coating Sample	*Absorptivity, α*	*Emissivity, ϵ*	$\alpha\epsilon$
Black chromium	0.868	0.088	9.8
Black nickel #1	0.877	0.066	13.3
Black nickel #2	0.867	0.109	8.0
Nextel black paint	0.967	0.967	1.0

Wax

Waxes are insulating coatings almost always applied by dipping the part completely in the wax and then trimming the wax to expose the areas to be plated. Special technology and skill are required for practical use of wax. These are best learned from the wax manufacturers and suppliers. One particular point: by judicious trimming of the wax the skillful operator can create a shield, which prevents excessive buildup at edges.

Shields and Robbers

Because of the high current densities used in chromium plating, "thieves" or "robbers" and shields are used more than in other plating procedures. The purpose of the electrical robber is to prevent burning or excess buildup of plate on corners and edges. Typically, a robber is a length of steel wire or rod, which is attached electrically to the part being plated and is placed (on the basis of experience) at an appropriate distance from the edge to be protected. The robber is so named because it receives the plate that would otherwise have built up on the edge of the workpiece, producing an undesirable result.

A shield is an insulating material used to alter the distribution of the electric field between the anodes and cathodes (parts). It can be shown mathematically that a shield should be positioned one-half as far away as the thief or robber from the surface it is protecting. The practical plater should be familiar with both techniques, as both have advantages and neither is satisfactory in all applications.

SPECIALTY CHROMIUM BATHS

Trivalent Chromium

Although chromium was historically first plated out of trivalent baths it has only been in recent years that commercial decorative systems have been developed. (These baths are described under Decorative Chromium.) Since the present trivalent chemistries can only plate thicknesses of a few tenths of a mil, they cannot at present be utilized for applications requiring functional or hard chromium thicknesses or properties.

Black Chromium

This process has received a moderate amount of attention over the last 15 years due to its usefulness as an energy-absorbing surface in solar collectors. Black chromium has a high absorption (α) for solar energy and a low emissivity (ϵ), that is, low reradiation back to the outside. Comparison values for several materials are given in Table V.

Because of outstanding durability and resistance to high temperatures black chromium is favored over other finishes. With improved techniques black chromium can provide consistent and reproducible absorption values of 0.90 to 0.95 and can maintain low emittance levels of 0.10 (250°F). Thermal stability up to 400°C (752°F) has been demonstrated.

In addition to solar energy applications black chromium is used as a black electroplated finish on decorative parts and parts requiring low reflectivity. Black chromium can be obtained from a number of published formulations, some of which are given in the article on Decorative Chromium Plating.

Table VI. Porous Chromium Plating

Type of Porosity	*Concentration (CrO_3, g/L)*	*Ratio*	*Temperature (°F)*	*Current density (A/in^2)*
Pit	250	100:1	122	3–4
Channel	250	115:1	140	3–4

Porous Chromium

During World War II, "porous chromium" plate came into prominence through its use on piston rings and cylinder bores of aircraft and diesel engines. It is applied on original equipment and for salvage of worn cylinders. Porous chromium plate may be described as a regular hard chromium plate approximately 0.004 in. or more thick, made especially resistant to scoring, seizing, or galling in wear-resistant applications, or given better lubricating qualities, by virtue of its having an "interrupted" surface made up of a series or collection of indentations and prominences, which are produced by various methods. Porous chromium has been found of value wherever borderline lubrication conditions are encountered, or where "breaking-in," to assure proper seating of working parts is necessary.

Three principal types of porous chromium plate are used. One is referred to as the "mechanical" type, which is produced by hard chromium plating over a roughened, cut, or engraved basis metal. The other two, produced by chemical or electrochemical etching of the chromium deposit, are referred to as the "pit" and "channel" types. A fourth type, which is also used, consists of etching pits into the surface of the finished chromium deposit through holes in a plastic mask.

With the etching methods, the porosity is produced by etching the chromium deposit, which has been suitably predisposed to the desired type porosity by proper correlation of plating conditions, bath composition (specifically CrO_3/SO_4 ratio), and plating temperature as shown in Table VI.

The newer, self-regulating, high-speed baths are also used for both types of porosity and offer advantages in ease of control, speed of plating, and hardness of deposit. The deposits, whether predisposed to the pit or channel type, may be etched by any of several methods. The one most generally used has been anodic treatment in a chromic acid solution. The extent of etching is important, but may vary considerably depending on the result to be accomplished; i.e., whether the etching is for porosity development alone or also for reducing plate thickness for dimensional requirements.

While chromium must be plated to close tolerances regardless of the type of porosity, it always requires a final finishing operation such as honing, lapping, grinding, or polishing. This operation removes approximately 0.001 in., or less, with the mechanical-type or channel-type porosity, to give a smooth solid surface of chromium with "plateaus" of suitable size. In the case of pit-type porosity the honing or finishing removes a greater thickness in the form of a loose crust of etched chromium to leave a chromium surface interspersed with pits, the extent and number of pits depending on the amount of etching and honing. In some applications, aircraft cylinders for example, the porous chromium plate must be specially cleaned after honing to remove fine particles of chromium or honing debris left in the pits or grooves from the finishing operation. Such final cleaning is usually done by vapor blasting.

Others

In recent years two additional proprietary chemistries have been marketed. Both are similar to the nonfluoride high-speed chemistry. The first one is used primarily for cast iron substrates where not all of the substrate is to be plated. This chemistry reduces the rate of attack by chromic acid on the exposed cast iron surface thereby reducing the rate of iron contamination into the plating bath. The second chemistry is capable of supporting plating current densities in excess of 10 A/ft^2. This chemistry has a plating efficiency of about 28% and allows for very rapid deposition rates.

ENVIRONMENTAL CONCERNS

Air Handling

Copious quantities of hydrogen are evolved at the cathode and of oxygen at the anode during chromium plating. As these gases break the surface of the bath they carry with them the bath constituents, especially chromic acid, as a mist. This mist must be entirely contained either at the bath surface by a mist suppressant or by a good tank ventilation system coupled to a certified, properly maintained EPA-approved emission control device such as a mist eliminator and pack bed scrubber. Heavy fines can be levied by OSHA for chromic acid mists escaping from the tank into the workplace and by the EPA for mists leaving the building.

The use of stable surface active agents as fume suppressants is an easy way to reduce the environmental and workplace safety hazards associated with misting. These agents act principally by lowering surface tension to reduce the size of evolved gas bubbles resulting in less solution travel when the bubbles break. Commercial practice does not support the concern that fume suppressants may cause an increased tendency for pitting. As most fume suppressants will generate some level of foam on the solution surface it is important that this foam layer be free from accumulated grease or oily residues, which could attach to a part lowered into the solution and result in pitting.

Care should also be taken that sparks from poor bus bar-to-rack connections do not occur since the foam blanket usually contains significant entrained hydrogen gas, which can explode if they come in contact with each other.

A recently introduced proprietary fume suppressant largely eliminates the foam blanket. This results in less accumulation of foreign materials at the surface, improved evaporation rates, and less probability of hydrogen explosions.

Impurity Removal From a Plating Bath

The slow but persistent buildup of cationic impurities, such as iron, copper, zinc, and aluminum in a chromium bath has historically been the life-limiting step for a solution. As these impurity levels exceed a combined total of 1 to 2 oz/gal (including trivalent chromium), poorer quality deposits will result. The solution conductivity will also be reduced, eventually limiting the current that can be passed by a given rectifier voltage. Until recent years the only solution to this dilemma was to dump all or a portion of a bath and remake with new chemistry. Presently, two alternatives to dumping are available—ion exchange and electrodialysis. Ion-exchange techniques are probably best used as a batch treatment or in a continuous mode to treat rinsewaters. This is due to the necessity to first dilute the bath chemistry approximately 50%, then cation exchange it (all active constituents of nonself-regulating hard chromium baths are anions), and then evaporate off water until the original concentration is reestablished. Electrodialysis is a technique probably best suited to continuously maintaining a low impurity level. It works, frequently in the tank itself, by having the cationic impurities move under the influence of potential and concentration gradient through a cation-selective membrane. On the other side, they are removed either by plating out on a cathode or by being precipitated as a hydroxide. As more and more shops are moving toward a closed-loop water system, these impurity removal technologies will become increasingly important to functional chromium platers.

Regulations

Air, water, and solid emissions from chromium plating facilities are all subject to regulations at the federal, state, and frequently local levels. OSHA also regulates in-plant worker exposure levels to chromic acid. These regulations are constantly being updated and need to be frequently reviewed for compliance by plating shops.

At the present time the regulations are those written by the U.S. EPA and which became effective in 1997. The minimum air emission standards for hard chromium plating tanks are divided into two classes. For small existing platers (<60,000 A) the amount of hexavalent chromium that may exit the exhaust stack of the tank is 0.03 milligram per cubic meter of air. For large existing shops and new or renovated shops the limit is 0.015 milligram hexavalent chromium per cubic meter of air. States and/or local districts may have lower limits. These limits and the compliance permits and documentation are constantly under revision. It is necessary to check the current status for the local area in which one operates a plating facility.

OSHA presently limits worker exposure to 0.1 milligram of chromic acid per cubic meter air on an 8-hr time-weighted average. This limit is presently under review by OSHA and may soon be significantly lowered.

COPPER PLATING

by Romualdas “Ron” Barauskas

Shipley Ronal Inc., Freeport, N.Y.

COPPER CYANIDE BATHS

Copper cyanide plating, with its accompanying health hazard and waste disposal problems (also shared with other cyanide plating baths), is still essential in many plating operations as a strike and, to a decreasing extent, for thick deposits. In dealing with the chemistry of the copper cyanide bath, a distinction must be made between total cyanide and free cyanide. Cuprous cyanide must be complexed with either potassium or sodium cyanide to form soluble copper compounds in aqueous solutions. The major complexed form is considered to be either potassium copper cyanide, $K_2Cu(CN)_3$, or sodium copper cyanide, $Na_2Cu(Cn)_3$. The sum of that required for the complexation of copper cyanide plus the amount of cyanide required for the proper functioning of the bath (free cyanide) is the total cyanide. The total cyanide required by weight is given in the following equation:

$$\text{Total potassium cyanide} = (\text{Copper cyanide required} \times 1.45) + \text{free potassium cyanide required}$$

$$\text{Total sodium cyanide} = (\text{Copper cyanide required} \times 1.1) + \text{free sodium cyanide required}$$

As an example:

A plating bath needs 2.0 g/L of copper cyanide and 0.5 g/L of free potassium cyanide. How much potassium cyanide is required for the bath?

$$\text{Total potassium cyanide} = (2.0 \times 1.45) + 0.5 = 3.4 \text{ g/L}$$

The plating bath formulations provided here are suitable for the majority of uses in cyanide copper plating and are easy to control. These formulations can be modified by the plater after reading the operating parameters and notes on maintenance and control. It is recommended, whenever possible, that the potassium formulations be used for extended plating range and a greater tolerance to deviation from recommended operating parameters.

Anodes for all baths should be high purity copper that is oxide free. They can be bagged copper slabs or bagged steel baskets containing copper nuggets. Plain steel anodes may be mixed with the copper to control copper cyanide content if copper content in the plating bath tends to increase with use. Anode/cathode ratio should be 1:1 to 2:1.

General Purpose Strike

The general purpose strike (see Table I) is used for improved adhesion, activation of passive substrates, or as an insurance step in the cleaning cycle. When used for zinc die castings, the hydroxide concentration should be kept at a maximum of 3.75 g/L (0.5 oz/gal). Deposits are usually in the range of 0.5–2.0 μm (0.02–0.08 mil) in thickness.

Strike-Plate Bath

The strike-plate bath (see Table II) is the one most used for the plating of zincated aluminum. It is also used for zinc die castings and other metals that are subject to attack by subsequent plating baths or finishing operations that require more than a strike deposit for


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Table I. General Purpose Copper Cyanide Strike

	Potassium	*Sodium*
Copper cyanide	30.0 g/L (4.0 oz/gal)	30.0 g/L (4.0 oz/gal)
Total potassium cyanide	58.5 g/L (7.8 oz/gal)	—
Total sodium cyanide	—	48.0 g/L (6.4 oz/gal)
Potassium hydroxide	3.75–7.5 g/L (0.5–1.0 oz/gal)	—
Sodium hydroxide	—	3.75–7.5 g/L (0.5–1.0 oz/gal)
Potassium carbonate	15.0 g/L (2.0 oz/gal)	—
Sodium carbonate	—	15.0 g/L (2.0 oz/gal)
Rochelle salt	30.0 g/L (4.0 oz/gal)	30.0 g/L (4.0 oz/gal)
Free potassium cyanide by analysis	11.25–15.0 g/L (1.5–2.0 oz/gal)	—
Free sodium cyanide by analysis	—	11.25–15.0 g/L (1.5–2.0 oz/gal)
Temperature	24–66°C (75–140°F)	
Current density	0.5–4 A/dm^2 (5–40A/ft^2)	
Time	30 sec to 2 min or until fully covered	
Cathode efficiency	30–60%	
Recommended agitation	None or mechanical	

protection. This formulation eliminates the need for two baths—a strike followed by a plate in a high efficiency bath. Deposits range from 3.0 to 5.0 μm (0.12–0.20 mil) in thickness for the parameters given in the formulation.

High-Efficiency Bath

The high-efficiency bath (see Table III) is used when a rapid buildup of a significant copper thickness is required. The copper cyanide can be as high as 120.0 g/L (16.0 oz/gal) for applications such as wire plating. Although the brightness and grain refinement of the deposit can be improved by the use of periodic reverse current or current interruption, the best results are obtained by using suitable additives.

Barrel Plating

The strike bath, high-efficiency bath, or both in combination, can be used for barrel plating. Typical compositions for barrel plating are shown in Table IV.

Table II. Copper Cyanide Strike-Plate Bath

	Potassium	*Sodium*
Copper cyanide	42.0 g/L (5.6 oz/gal)	42.0 g/L (5.6 oz/gal)
Total potassium cyanide	66.6 g/L (8.9 oz/gal)	—
Total sodium cyanide	—	51.9 g/L (6.9 oz/gal)
Potassium carbonate	30.0 g/L (4.0 oz/gal)	—
Sodium carbonate	—	30.0 g/L (4.0 oz/gal)
Rochelle salt	60.0 g/L (8.0 oz/gal)	60.0 g/L (8.0 oz/gal)
Free potassium cyanide by analysis	5.7 g/L (0.8 oz/gal)	—
Free sodium cyanide by analysis	—	5.7 g/L (0.8 oz/gal)
pH	10.2–10.5	
Temperature	40–55°C (100–130°F)	
Current density and time	Initial (strike) 2.5–3.0 A/dm^2(25.0–30.0 A/ft^2) for 2 min. Final (plate)1.0–1.5 A/dm^2 (10.0–15.0A/ft^2) for 3–5 minutes.	
Cathode efficiency	30–50%	
Recommended agitation	None or mechanical	

Use diluted tartaric acid or acetic acid to lower the pH; hydroxide to raise it.

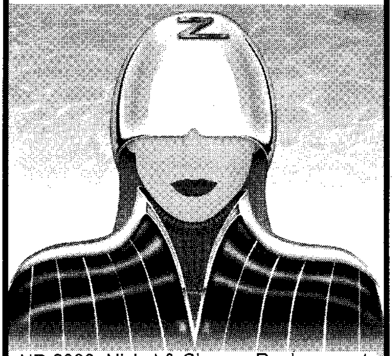

Table III. High-Efficiency Copper Cyanide Bath

	Potassium	*Sodium*
Copper cyanide	60.0 g/L (8.0 oz/gal)	75.0 g/L (10.0 oz/gal)
Total potassium cyanide	102.0 g/L (13.6 oz/gal)	—
Total sodium cyanide	—	97.5 g/L (13.0 oz/gal)
Potassium carbonate	15.0 g/L (2.0 oz/gal)	—
Sodium carbonate	—	15.0 (2.0 oz/gal)
Potassium hydroxide	15.0 g/L (2.0 oz/gal)	—
Sodium hydroxide	—	15.0 g/L (2.0 oz/gal)
Rochelle salt	45.0 g/L (6.0 oz/gal)	45.0 g/L (6.0 oz/gal)
Free potassium cyanide by analysis	15.0 g/L (2.0 oz/gal)	—
Free sodium cyanide by analysis	—	15.0 g/L (2.0 oz/gal)
Temperature	60–71°C (140–160°F)	
Current density	up to 80 A/ft^2	
Cathode efficiency	90–99%	
Recommended agitation	Mechanical, solution or air	

Bath Preparation

Dissolve potassium or sodium cyanide in cold water. In a separate container, mix copper cyanide with water to form a thin slurry and slowly add to the potassium or sodium cyanide solution while mixing. The dissolving reaction is exothermic and the solution should not be allowed to overheat, as this may decompose some of the free cyanide. Add the rest of the required materials after dissolving the copper cyanide. Carbon treatment of the bath before use is recommended. All salts should be sulfur free to prevent dull, red deposits in low current density plating areas.

Maintenance and Control

Constituents

It is recommended that all constituents in the formulation be controlled to within 10% of their nominal values, especially the free cyanide. The copper cyanide concentration controls the allowable plating current density in combination with agitation. The free cyanide concentration controls efficiency, plating range, throwing power, and anode polarization. The hydroxide concentration controls conductivity and throwing power. Carbonates buffer the solution and reduce anode polarization. Although high carbonate concentration of 90.0 to 120.0 g/L (12.0–16.0 oz/gal) decreases the plating range, it is added to new baths to stabilize

Table IV. Copper Cyanide Baths for Barrel Plating

	Potassium	*Sodium*
Copper cyanide	45.0–60.0 g/L (6.0–8.0 oz/gal)	45.0–60.0 g/L (6.0–8.0 oz/gal)
Total potassium cyanide	80.3–109.5 g/L (10.7–14.0 oz/gal)	—
Total sodium cyanide	—	64.5–88.5 g/L (8.6–11.8 oz/gal)
Potassium carbonate	15.0 g/L (2.0 oz/gal)	—
Sodium carbonate	—	15.0 g/L (2.0 oz/gal)
Potassium hydroxide	7.5–22.5 g/L (1.0–3.0 oz/gal)	—
Sodium hydroxide	—	7.5–22.5 g/L (1.0–3.0 oz/gal)
Rochelle salt	45.0 g/L (6.0 oz/gal)	45.0 g/L (6.0 oz/gal)
Free potassium cyanide by analysis	15.0–22.5 g/L (2.0–3.0 oz/gal)	—
Free sodium cyanide by analysis	—	15.0–22.5 g/L (2.0–3.0 oz/gal)
Temperature	60–71°C (140–160°F)	

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their initial operation. Rochelle salt enhances anode corrosion and provides some grain refinement. Potassium formulations have a broader plating range than sodium formulations.

Temperature

Temperature above 71°C (160°F) in the high-efficiency and barrel formulations promotes the breakdown of cyanide and the rapid buildup of carbonates.

Agitation

Mechanical and/or solution agitation is recommended. Use air agitation only when required, as air agitation promotes carbonate buildup.

Contamination

Organic contamination causes nonuniform, dull, rough, or pitted deposits. In severe cases of organic contamination, the anodes may polarize. Carbon treatment will remove organic contamination. A copper strike should not be considered to be a cleaner and should be carbon treated periodically to prevent organic contamination from spreading to other plating baths. Hexavalent chromium contamination causes skip plate in the low current density plating area, blisters, and nonuniform deposits.

The best method for eliminating the problem of chromium contamination is to eliminate the source. Hexavalent chromium in the bath can be reduced to trivalent by using proprietary reducing agents. Zinc contamination causes nonuniform or brass-colored deposits and can be removed by dummying the bath at 0.2–0.4 A/dm^2 (2–4 A/ft^2). Sulfur and its compounds cause dull, red deposits in the low current density plating areas and usually appear in new baths because of impure cyanides or leaching from tank linings. Small amounts of a zinc salt, such as zinc cyanide, will eliminate sulfur red from the deposits. Most other common types of metallic contamination cause deposit roughness and can usually be removed by dummying and filtration.

Carbonate

Excessive sodium carbonate can be removed by freezing out at a low temperature because of its limited solubility below −3°C (26°F). Both potassium and sodium carbonate can be removed by precipitation with calcium oxide, calcium hydroxide, or calcium sulfate.

COPPER PYROPHOSPHATE PLATING BATHS

Copper pyrophosphate plating baths require more control and maintenance than cyanide baths; however, the solutions are relatively nontoxic. The main uses of copper pyrophosphate baths have been for electroforming, plating on plastics, and printed circuits.

The chemistry involved in copper pyrophosphate plating is the formation of potassium copper pyrophosphate complex [$K_6Cu(P_2O_7)_2 \cdot 6H_2O$] from copper pyrophosphate ($Cu_2P_2O_7 \cdot 3H_2O$) and potassium pyrophosphate ($K_4P_2O_7$). The ratio of pyrophosphate ($P_2O_7^{4-}$) to copper (Cu^{2+}) in the compound is 5.48 to 1. Any pyrophosphate in excess of this ratio is called "free" or "excess" pyrophosphate. Free or excess pyrophosphate is essential for the operation of the bath in providing conductivity and anode corrosion. This is done by running a pyrophosphate to copper (P_2O_7/Cu) ratio of 7:1 to 8:1 in the plating bath. A strike bath may have a higher ratio. Potassium pyrophosphate baths are recommended over sodium formulations for better conductivity and higher solubility of the potassium copper complex.

Anodes for all baths should be high purity copper that is oxide free. Anodes can be copper slabs or copper nuggets in titanium baskets. Anode bags are not recommended. Anode to cathode ratio should be 2:1. Copper pyrophosphate baths tend to build orthophosphate (HPO_4^{2-}) concentration by the hydrolysis of pyrophosphate. Small amounts of orthophos-

Table V. Pyrophosphate Copper Strike

Copper pyrophosphate ($Cu_2P_2O_7{\cdot}3H_2O$)	25.0–30.0 g/L (3.3–4.0 oz/gal)
Potassium pyrophosphate ($K_4P_2O_7$)	95.7–176.0 g/L (12.8–23.4 oz/gal)
Potassium nitrate	1.5–3.0 g/L (0.2–0.4 oz/gal)
Concentrated ammonium hydroxide	0.5–1 ml/L
pH	8.0–8.5
Temperature	22–30°C (72–86°F)
Current density	0.6–1.5 A/dm^2 (6.0–15.0 A/ft^2)
Agitation	Mechanical and air
Filtration	Continuous
Operating parameters by analysis are:	
Copper metal	9.0–10.7 g/L (1.2–1.4 oz/gal)
Pyrophosphate	63.0–107.0 g/L (8.4–14.2 oz/gal)
P_2O_7/Cu ratio	7:1 to 10:1

phate are not harmful; however, higher concentrations in excess of 100.0 g/L (13.3 oz/gal) may cause banded deposits with decreased plating range and conductivity in the standard plating baths.

In the printed circuit bath, the orthophosphate concentration should not be allowed to exceed 40.0–60.0 g/L (5.5–8.0 oz/gal) because, beyond this point, there is a decrease in both the throwing power of the solution and ductility of the deposit. Orthophosphate concentration is lowered by dilution or replacement of the bath. The anode and cathode efficiencies of copper pyrophosphate baths are essentially 100%. Maximum agitation is required for the best results. When using air agitation, the volume of air required should be 1 to 1.5 times the surface area to be plated. Ultrasonic agitation may also be used.

Strike

Copper pyrophosphate plating baths can form immersion coatings, similar to acid copper, on steel and zinc die castings, and cause poor adhesion. A cyanide- or pyrophosphate-copper strike is used for steel, and a cyanide strike for zinc is recommended. The pyrophosphate-copper strike is a diluted version of the plating bath, which can have a P_2O_7/Cu ratio of 10:1 or higher. A typical formulation would be as shown in Table V.

Typical Pyrophosphate Bath

The copper pyrophosphate bath formulation in Table VI can be used for all plating applications except printed circuits. Current interruption or periodic reverse current can further refine the grain structure.

Printed Circuit Bath

The use of nonproprietary or proprietary additives that improve the throwing power and ductility of deposit is recommended for printed circuit application. A typical formulation is shown in Table VII.

Copper pyrophosphate baths are sensitive to contamination, especially organic contamination, and are made from purified liquid concentrates.

Maintenance and Control

Constituents

Ammonia aids in anode corrosion and acts as a grain refiner. Ammonia is replenished daily because of evaporation loss. Nitrate increases the high current density plating range and is a cathode depolarizer. The pH is controlled by using pyrophosphoric acid or potassium hydroxide as required.

Table VI. Copper Pyrophosphate Bath for General Use

Copper pyrophosphate ($Cu_2P_2O_7 \cdot 3H_2O$)	52.5–84.0 g/L (7.0–11.2 oz/gal)
Potassium pyrophosphate ($K_4P_2O_7$)	201.1–349.1 g/L (26.8–46.5 oz/gal)
Potassium nitrate	3.0–6.0 g/L
Concentrated ammonium hydroxide	3.75–11.0 ml/L
pH	8.0–8.7
Temperature	43–60°C (110–140°F)
Current density	1.0–8.0 A/dm^2 (10.0–80.0 A/ft^2)
Agitation	Mechanical and air
Filtration	Continuous
Operating parameters by analysis are:	
Copper metal	18.8–30.0 g/L (2.5–4.0 oz/gal)
Pyrophosphate	131.6–225.0 g/L (17.5–30.0 oz/gal)
P_2O_7/Cu ratio	7.0:1–7.5:1

Temperature

Operating the baths above 60°C (140°F) causes the rapid hydrolysis of pyrophosphate to orthophosphate.

Agitation

Copper pyrophosphate baths need vigorous agitation for a normal operating current density plating range. The most common form used is air agitation, by itself or in combination with mechanical agitation. Ultrasonic and solution jet agitation can also be used.

Contaminants

Copper pyrophosphate baths are sensitive to organic contamination such as oil, breakdown products, or organic addition agents. Organic, cyanide, and lead contamination can cause dull, nonuniform deposits with a narrow plating range. Carbon treatment will remove organic contamination and treating with hydrogen peroxide or potassium permanganate before carbon treatment will remove cyanide and severe organic contamination. Lead can be removed by dummying.

Orthophosphate

In addition to high temperature, localized overheating or too low a pH can cause the rapid buildup of orthophosphate.

Table VII. Copper Pyrophosphate for Printed Circuits

Copper pyrophosphate ($Cu_2P_2O_7 \cdot 3H_2O$)	57.8–73.3 g/L (7.7–9.8 oz/gal)
Potassium pyrophosphate ($K_4P_2O_7$)	231.0–316.5 g/L (30.8–42.2 oz/gal)
Potassium nitrate	8.2–15.8 g/L (1.1–2.1 oz/gal)
Concentrated ammonium hydroxide	2.7–7.5 ml/L (0.3–0.75% by volume)
Addition agent	As required
pH	8.0–8.4
Temperature	49–54°C (120–130°F)
Current density	2.5–6.0 A/dm^2 (25.0–60.0A/ft^2)
Agitation	Mechanical and air
Operating parameters by analysis are:	
Copper metal	20.7–26.2 g/L (2.75–3.5 oz/gal)
Pyrophosphate	150.0–204.4 g/L (20.0–27.2 oz/gal)
P_2O_7/Cu ratio	7.2:1–7.8:1

OTHER ALKALINE BATHS

There has been work on the development of other types of alkaline, noncyanide copper plating baths; but their use in industry has been too specialized or limited to discuss at this time.

COPPER SULFATE BATHS

Copper sulfate baths are economical to prepare, operate, and waste treat. They are used in printed circuits, electronics, semiconductor, rotogravure, electroforming, decorative, and plating-on-plastics applications.

The chemistry of the solution is simple, with copper sulfate and sulfuric acid forming the ionized species in solution. The baths are highly conductive. Previous problems with throwing power have been overcome with the advent of the modern high throw formulations and additives. Steel parts must be cyanide copper- or nickel-plated in strike formulations to prevent immersion coatings and poor adhesion. Zinc die castings and other acid sensitive metals must have sufficient deposit to prevent attack by the sulfuric acid. The baths are operated at room temperature for most applications. Anodes should be phosphorized (0.02–0.08% by weight phosphorus), oxide-free, high-purity, rolled copper. Copper anode nuggets in titanium baskets can be used. Anodes should be bagged. The anode current density should range from 15 to 30 A/ft^2. Excessively high current densities can cause the anode to lose its black, protective film and cause rough deposits; excessively low current densities can cause copper sulfate buildup, which can cause a reduction in throwing power, and a thick anode film, which can reduce the anode's conductivity. Anode and cathode efficiencies are essentially 100%. Since copper sulfate plating has become of major importance to the industry, a troubleshooting guide is given in this section (see Table X).

Standard Acid Copper Plating

Table VIII lists the standard formulations for copper sulfate baths. Air agitation or solution sparging with or without mechanical agitation, is recommended.

High-Throw Bath

The formulation shown in Table IX is used in printed circuit, barrel plating, and other applications where high throwing power is required.

For circuit board plating, copper is most commonly plated following an electroless copper metallization of the through holes. Recently, a number of technologies have been developed that replace the electroless copper with other means of imparting conductivity to the through holes. They fall into two general categories: carbon-based and palladium-based systems. They use conventional acid copper sulfate electrolytes to plate up through the holes.

Pulse and periodic reverse plating are being used to improve throwing power, deposit characteristics, and productivity with the development of specialized additives. New additives have been developed with DC current to maintain throwing power at higher cathode current densities, improving productivity.

Bath Preparation

Baths can be made by dissolving copper sulfate in water and then adding sulfuric acid. Carbon treatment is recommended. Cooling to room temperature is recommended prior to adding proprietary additives. Baths can also be made using either purified liquid copper

Table VIII. Standard Acid Copper Baths

General formulation:	
Copper sulfate	26–33 oz/gal (195–248 g/L)
Sulfuric acid	4–10 oz/gal (30–75 g/L)
Chloride	50–120 ppm[a]
Current density	20–100 A/ft^2
Semibright plating (Clifton-Phillips):	
Copper sulfate	33 oz/gal (248 g/L)
Sulfuric acid	1.5 oz/gal (11 g/L)
Chloride	50–120 ppm[a]
Thiourea	0.0001 oz/gal (0.00075 g/L)
Wetting agent	0.027 oz/gal (0.2 g/L)
Bright plating (Beaver):	
Copper sulfate	28 oz/gal (210 g/L)
Sulfuric acid	8 oz/gal (60 g/L)
Chloride	50–120 ppm[a]
Thiourea	0.0013 oz/gal (0.01 g/L)
Dextrin	0.0013 oz/gal (0.01 g/L)
Bright plating (Clifton-Phillips):	
Copper sulfate	26.5 oz/gal (199 g/L)
Sulfuric acid	4 oz/gal (30 g/L)
Chloride	50–120 ppm[a]
Thiourea	0.005 oz/gal (0.0375 g/L)
Molasses	0.1 oz/gal (0.75 g/L)

[a] 10 ml of reagent grade concentrated hydrochloric acid per 100 gallons is equivalent to 12 ppm.

sulfate (generally around 36 oz/gal as copper sulfate pentahydrate) or commercial premade solutions without the organic additives. Carbon polishing is recommended prior to adding proprietary additives.

Maintenance and Control

Constituents

Copper sulfate is the source of copper ions in solution. Because the anode and cathode efficiencies normally are close to 100%, the anodes replenish the copper ions so that the copper concentration remains fairly stable in solution. The sulfuric acid increases the conductivity of the solution and reduces the anode and cathode polarization. It prevents precipitation of basic salts and improves throwing power. In high throw formulations, the weight ratio of copper metal to sulfuric acid should be maintained at less than 1:10. To further enhance the throwing power, the copper sulfate may be reduced to 6.0–8.0 oz/gal (45.0–60.0 g/L) to give metal-to-acid ratios as high as 1:30. This may be useful in plating high aspect ratio printed circuit boards; however, the lower copper content decreases the allowable plating current densities and increases the plating times. Copper sulfate is reduced in concentration

Table IX. High-Throw Acid Copper Bath

Copper sulfate	8.0–10.0 oz/gal (60.0–75.0 g/L)
Sulfuric acid	25.0–30.0 oz/gal (187–225 g/L)
Chloride	50–100 ppm[a]
Proprietary additive(s)	Per vendor recommendations

[a] 10 ml of reagent grade concentrated hydrochloric acid per 100 gallons is equivalent to 12 ppm.

in high throw formulations to prevent common ion precipitation effects as the sulfuric acid is increased. Sulfuric acid concentrations above 11% by volume begin to reduce cathode efficiency. Chloride ion, in bright and high throw baths, reduces anode polarization and eliminates striated deposits in the high current density areas.

Temperature

These baths are operated at room temperature for the majority of applications. If the temperature is too low, cathode efficiency and plating range will be reduced. Baths used where bright deposits in the low current density are not required may be operated at temperatures as high as 50°C (120°F) to increase the plating range in electroforming, printed circuit, or rotogravure applications.

Agitation

Air, mechanical, solution jet, or rotating work agitation can be used. The more vigorous the agitation, the broader the allowable plating current density.

Contaminants

Organic contaminants are the ones most commonly dealt with in acid copper plating. Major sources are decomposition products of brighteners, drag-in of previous process chemistries, tank liners, unleached anode bags, stop-offs, resists, and impure salts or acid. Contaminants will adversely affect the appearance and the physical properties of the deposit.

A green coloration of the bath indicates significant organic contamination. Organic impurities are removed by treatment with activated carbon. In cases of severe contamination, potassium permanganate, hydrogen peroxide, or even bleach, if the chloride ion is monitored, may be necessary to break down the organics so that the activated carbon can effectively remove them. Carbon itself may contaminate or have no effect if the activated carbon was not designed for use in high acid baths. Cellulose filter aids should not be used.

Some common metallic contaminants and their effects are as follows:

Antimony (10–80 ppm): rough, brittle deposits. Gelatin or tannin added to the bath will inhibit its codeposition.
Arsenic (20–100 ppm): same as antimony.
Bismuth: same as antimony.
Cadmium (>500 ppm): can cause an immersion deposit and polarization of the anode during idle time. Can tie up chloride ions.
Iron (>1,000 ppm): reduces bath conductivity and throwing power.
Nickel (>1,000 ppm): same as iron.
Selenium (>10 ppm): anode polarization, roughness.
Tellurium (>10 ppm): same as selenium.
Tin (500–1,500 ppm): immersion deposits and polarization of anodes during idle time.
Zinc (>500 ppm): same as cadmium.

A guide for troubleshooting acid copper baths is given in Table X.

COPPER FLUOBORATE BATH

This bath allows the use of high current densities and increased plating speed, as copper fluoborate is extremely soluble and large amounts can be dissolved in water. The main

Table X. Troubleshooting Guide for Acid Copper Sulfate Plating

Problem	*Cause*	*Corrective Action*
High current density burning	Low copper, high acid	Analyze and adjust
	Low temperature	Heat bath
	Insufficient agitation	Lower current, unless agitation can be improved
	Organic contamination	Carbon treat
	Low chloride (bright baths)	Analyze and adjust
Loss of brightness (in bright formulations)	Low additive	Determine addition by Hull cell
	Organic contamination	Carbon treat
	Low chloride	Analyze and adjust
	High temperature	Cool the bath
	Low copper	Analyze and adjust
Rough deposit	Particles in solution	Filter bath
	Torn anode bags	Replace torn bag
	Improper anodes	Use phosphorized copper anodes
	Low chloride	Analyze and adjust
Pitting	Organic contamination	Carbon treat
	Anode slough	Bag anodes
	Low chloride	Analyze and adjust
Poor distribution	Low or nonuniform agitation	Improve and adjust
	Excessive anode area	Adjust
	Improper anode film	Dummy
	Current supply AC ripple	Adjust to below 10%
	Organic contamination	Carbon treat
Low current	Organic contamination	Carbon treat
	Low sulfuric acid	Analyze and adjust
	Low additive	Determine addition by Hull cell
	High chloride	1. Wash off anode film and dummy to reform film 2. Precipitate with silver sulfate or nitrate and carbon filter 3. Dilute
	Current density too low	Increase current
	High temperature	Cool bath
Anode polarization	Tin, gold contamination	Dummy with a copper foil (no current)
	Low temperature	Heat bath
	Improper anodes	Bright baths require phosphorized anodes
	High chloride	1. Wash off anode film and dummy to reform film 2. Precipitate with silver sulfate or nitrate and carbon filter 3. Dilute
	High sulfuric acid	Analyze and dilute bath
	Low copper sulfate	Analyze and adjust
	Organic contamination	Carbon treat

Table XI. Copper Fluoborate Baths

	High Concentration	*Low Concentration*
Copper fluoborate	60 oz/gal (459 g/L)	30 oz/gal (225 g/L)
Fluoboric acid	5.4 oz/gal (40.5 g/L)	2 oz/gal (15 gal/L)
pH (colorimetric)	0.2–0.6	1.0–1.7
Temperature	65–150° F	65–150° F
Baumé	37.5–39.5°	21–22°
Current density	125–350 A/ft^2	75–125 A/ft^2

drawback is its corrosivity, consequently, construction materials are normally limited to hard rubber, polypropylene, polyvinyl chloride (PVC), and carbon/Karbate. In all other aspects, the copper fluoborate bath is similar to copper sulfate plating.

The anodes should be high-purity copper that is oxide free. Anode bags should be made of Dynel or polypropylene. Normally, the bath is made up with copper fluoborate concentrate (1.54 g/ml or 50.84°Bé), which contains 92.0 oz/gal cupric fluoborate (26.9% by weight copper metal), 1.4 oz/gal fluoboric acid, and 2 oz/gal boric acid (to prevent the formation of free fluoride due to fluoborate hydrolysis). The fluoboric acid (1.37 g/ml or 39.16°Bé) typically contains 90 oz/gal of fluoboric acid and 0.9 oz/gal of boric acid.

Typical formulations for copper fluoborate baths are given in Table XI.

Maintenance and Control

Contaminants

Organic contaminants can affect the deposit appearance/uniformity and mechanical properties, especially ductility. These can be removed by carbon treatment. Cellulose filter aids, free of silica, can be used. These baths are often carbon filtered continuously. Lead is the only common metallic contaminant that causes problems, and it can be precipitated with sulfuric acid.

Additives

Normally, no organic additives are used. Molasses can harden deposits and minimize edge effects. Some of the same additives (e.g., acetyl cyanamide) used for copper sulfate baths can also be used with the fluoborate formulations.

GOLD PLATING

by Alfred M. Weisberg

Technic Inc., Providence, R.I.

All types of gold and gold alloy electroplates are used for many different applications by many different industries; however, there are eight general classes that may be listed that include much of present-day gold plating:

Class A—Decorative 24K gold flash (2–4 millionths of an in.), rack and barrel.
Class B—Decorative gold alloy (2–4 millionths of an in.), rack and barrel.
Class C—Decorative gold alloy, heavy (20–over 400 millionths of an in.), rack. These deposits may be either C-1 karat color or C-2 karat assay.
Class D—Industrial/electronic high-purity soft gold (20–200 millionths of an in.), rack, barrel, and selective.
Class E—Industrial/electronic hard, bright, heavy 99.5% gold (20–200 millionths of an in.), rack, barrel, and selective.
Class F—Industrial/electronic gold alloy, heavy (20–over 400 millionths of an in.), rack and selective.
Class G—Refinishing, repair and general, pure, and bright alloy (5–40 millionths of an in.), rack and selective brush.
Class H—Miscellaneous, including electroforming of gold and gold alloys, statuary and architectural, etc.

To further simplify an enormous and diverse subject, gold and gold alloy plating solutions may be considered to belong to five general groups:

Group 1—Alkaline gold cyanide for gold and gold alloy plating; Classes A–D and occasionally F–H.
Group 2—Neutral gold cyanide for high-purity gold plating; Classes D and G.
Group 3—Acid gold cyanide for bright, hard gold and gold alloy plating; occasionally Classes B, C, E–G.
Group 4—Noncyanide, generally sulfite, for gold and gold alloy plating; occasionally Classes A–D and F–H.
Group 5—Miscellaneous.

There are literally hundreds of formulations within these five classes of gold plating solutions.

Physical, engineering, or aesthetic considerations will determine which of these groups should be considered for a particular job, but economics will usually be the determining factor in selecting a specific formulation and plating method. The price of gold per troy ounce is only one aspect of the economics that must be considered in deciding among rack, barrel, brush, continuous, or selective plating. For any individual applications it is necessary to balance and optimize the following variables:

1. *Cost of the bath.* This includes the volume necessary for a particular method and the gold concentration.
2. *Speed of plating. and the bath and the cost for a given desired production.*
3. *Cost of drag-out loss.* This will depend on the gold concentration used; the shape of the part; whether it is rack, barrel, continuously, or selectively plated; and must include the probable recovery of dragged-out gold by electrolytic or ion-exchange recovery.

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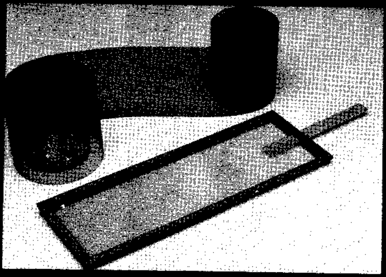

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4. *Cost of control and maintenance.* Some high-speed and high-efficiency baths require almost constant attendance and analysis.
5. *Cost of longevity of the bath.* High-speed and especially high-purity baths with good drag-out recovery must be changed periodically to maintain purity. This results in a certain loss on changeover.
6. *Cost of money* (interest) to keep the bath.
7. *Initial cost of the equipment.*
8. *Overhead cost of the equipment* (whether it is operating or not operating), that is, the interest cost per hour or per day.

Sometimes, a simple manual rack or barrel method will be cost-effective; at other times, a high-speed fully automated plant is justified.

Gold today is a freely traded commodity with a different price every day. To plate successfully it is necessary to watch and control costs.

DECORATIVE GOLD PLATING (Classes A–C and, sometimes, G)

Much, but not all, decorative plating is applied to jewelry, watch attachments, and other items of personal use and adornment. The thicknesses of gold or gold alloy are usually 0.000002 to 0.000005 in. and the time of plating is 5 to 30 sec. The recommended trade practice rules for the jewelry industry require that this deposit be called gold flash or gold wash. (To be called gold electroplate it is necessary to have a minimum of 0.000007 in.) These deposits are usually applied over a bright nickel underplate and are bright as plated. They do not require any brightening or grain-refining agents. There are hundreds of different colors and hues, but the Class A and B baths, shown in Table I, will give a representative sample of colors.

All of the "coloring" baths in Table I should use 316 stainless steel anodes. The ratio of anode to cathode area is best at 1:1 or 3:1. Very high ratios, when the tank is used as an anode, tend to give an uneven color and thickness of deposit, and the end pieces will frequently burn. No agitation should be used to ensure a uniform color. Sliding or tapping on the cathode bar will increase the deposition of gold and make each color richer but will quickly deplete gold and unbalance the bath. Gold and alloying metals should be added periodically, based on ampere-hour (A-hr) meter readings. The baths, with the exception of the white, green, and rose solutions, should operate at approximately 6% cathode current efficiency. Every 11 A-hr of operation 5 g of gold should be added, together with the proper amount of alloy.

All operating conditions should be controlled as closely as possible. Any variation of the conditions will affect the cathode current efficiency of the gold or the alloy, or both. Changes in the amount of the metals deposited will change the color of the deposit. Other factors that will alter the color of the deposit are the following:

1. *Surface finish.* The surface finish of the basis metal will change the apparent color of the deposit. This is particularly noticeable when a single item has both bright and textured areas. Plated in the same bath, they will appear to be two different colors.
2. *Color of basis metal.* The color of the basis metal alters the color of the gold deposit by adding its color to the gold until the deposit is sufficiently thick to obscure the base. Most gold alloy deposits, if properly applied, will obscure the base after 2½ millionths of an in. have been applied. Proprietary additives will allow the gold to obscure the base with as little as 1½ millionth of an in. to allow richer colors with the use of less gold.
3. *Current density.* Too low a current density tends to favor the deposition of gold and causes the alloy to become richer. Too high a current density at first favors the alloy and pales out the color. Raising the current density further causes the development of pink, orange, or red tones.
4. *Free cyanide.* Solutions containing copper are very sensitive to changes in the free cyanide content. Low cyanide causes an increase in the pink and red shades, and high cyanide significantly increases the yellow by holding back the copper.

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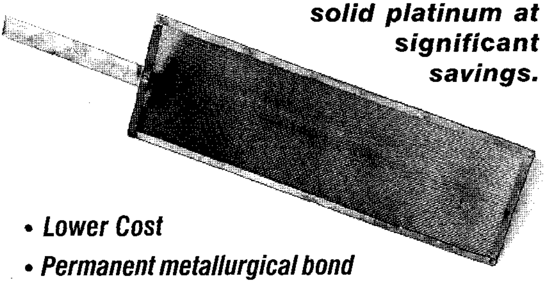

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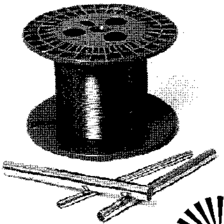

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Table I. Gold and Gold Alloy Flash Baths (Classes A and B)

	24K or English	*Low Cyanide English*	*Hamilton Colors*			*White No. 1*	*White No. 2*	*Green*	*Pink*	*Rose*
			Yellow	*Pink*	*Green*					
Gold as potassium gold cyanide (g/L)	1.25–2	1.25–2	1.25–2	1.25–2	1.25–2	0.4	0.325	2	0.82	6
Free potassium cyanide (g/L)	7.5	7.5	7.5	2.0	2.0	15	15	7.5	4	4
Dipotassium phosphate										
oz/gal	2	2	2	2	2	2	2	2	2	—
g/L	15	15	15	15	15	15	15	15	15	—
Sodium hydroxide (g/L)	—	—	—	—	—	—	—	—	—	15
Sodium carbonate (g/L)	—	—	—	—	—	—	—	—	—	30
Nickel as potassium nickel cyanide (g/L)	—	0.025–1.4	0.025	0.025	0.025	1.1	—	—	0.2	—
Copper as potassium copper cyanide (g/L)	—	—	0.13	1.1	—	—	—	—	2.7	—
Silver as potassium silver cyanide (g/L)	—	—	—	—	0.05	—	—	0.25	—	—
Tin (g/L)	—	—	—	—	—	—	2.1	—	—	—
Temperature (°F)	140–160	140–160	150–160	140–160	140–160	150–160	150–160	130–160	150–160	150–180
Current density (A/ft^2)	10–40	10–40	10–35	20–50	10–40	30–60	30–50	10–30	30–40	20–50

Table II. Antique Baths

	Bright Yellow Highlights, Orange-Brown Smut	*Green Highlights, Green-Black Smut*
Gold as $KAu(CN)_2$ (g/L)	6	2
Silver as potassium silver cyanide (g/L)	—	0.3
Sodium hydroxide (g/L)	15	—
Sodium carbonate (g/L)	30	—
Ammonium carbonate (g/L)	—	38
Sodium cyanide (g/L)	4	15
Temperature (°F)	160–180	70–90
Agitation	None	None
Current density (A/ft^2)	30–40	10

5. *Temperature.* The effect is similar to current density. Low temperatures favor the gold yellows, and higher temperatures favor the alloy colors. Temperatures over 160°F should be avoided, except in the case of rose golds, because of the rapid breakdown of cyanide and the darkening of the color.
6. *pH.* It is rarely necessary to adjust the pH of a gold or gold alloy bath. They are usually buffered between pH 10 and 11. Only pink, rose, or red golds are favored by higher readings.

BARREL PLATING (Classes A and B)

Gold as $KAu(CN_2)$, 0.4 g/L
Free cyanide as NaCN, 30 g/L
Disodium phosphate, 23 g/L
Temperature, 100–120°F
Anodes, stainless steel (1:1 or better)

In typical jewelry barrel plating about 6 V is necessary. A decorative finish of 0.000002 in. is deposited in 3 to 4 min. If the parts are small and densely packed in the barrel it may be necessary to plate up to 8 min to get even coverage.

The above formulation may be altered to achieve various colors. Champagne or light Hamilton colors may be achieved by adding 1.5 to 3 g/L of nickel. Lowering the temperature will also produce a lighter and more uniform color.

ANTIQUE GOLDS (Classes A and B)

The art of the 19th-century platers was to produce a finish that looked as if it had been mercury gilt over silver or copper (vermeil) and buried or weathered by the elements for a century or so. Each master plater developed an antique finish that was his trademark. The basic modern method to achieve this effect is as follows:

1. "Burn on" a dark smutty finish.
2. Relieve the highlights on a deeply recessed piece or the flat surface on a filigreed piece by either hand rubbing with pumice and sodium bicarbonate or wheel relieving with a cotton buff, tampico brush, or a brass or nickel-silver wheel. Other methods are possible.
3. Flash gold or a gold alloy deposit on the imperfectly cleaned highlights.

Typical formulations for antique gold baths are provided in Table II. The more the

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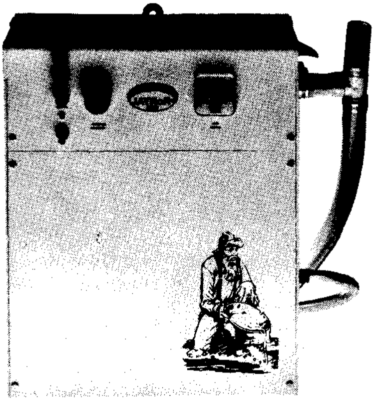

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Table III. A Selection of Typical Acid Gold Color Baths for Thick Deposits

	22k	*24k*	*Hamilton*		
	Yellow	*Yellow*	*1N*	*2N*	*3N*
Gold (g/L)	4–8	4–8	4–8	4–8	4–8
Conducting salts (g/L)	120	120	120	120	120
Nickel as nickel metal (g/L)	0.2	—	7–10	4–6	1–3
Cobalt as cobalt metal (g/L)	1	0.5	—	—	—
pH	4.0–4.5	4.4–4.8	4.0–4.2	4.0–4.2	4.0–4.2
Temperature (°F)	90–100	80–90	120–140	100–120	90–100
Current density (A/ft^2)	10–20	10–20	10–20	10–20	10–20
Agitation	Required	Required	Required	Required	Required

solutions in Table II are abused and the more the operator violates good plating practice and good cleanliness the better and more distinctive the finish will be.

An expensive finish requiring double-racking, but a beautiful finish, is Russian antique. This may be produced by relieving the green-gold antique in Table II and then flashing over with the 24K or English gold.

The old antique baths of the 1940s and 1950s that did not require double-racking or stringing are no longer practical because of the high price of gold.

HEAVY DECORATIVE GOLD (Classes C-1 and C-2)

It is necessary to distinguish between the actual karat assay of a gold alloy electroplate and the apparent karat color of the plate. In general a decorative karat deposit will appear to be a much lower karat than it actually will assay. A 14K color deposit may actually assay 20 to 21K. The formulas in Table III will deposit karat colors but will actually assay a higher karat. (In computing costs it is best to assume that the deposit is pure gold.)

INDUSTRIAL/ELECTRONIC GOLD PLATING

Gold is electroplated for many different electrical and electronic purposes; however, today the majority of gold plating is applied to three specific classes of components: semiconductors, printed/etched circuits, and contacts/connectors. The requirements for the deposit of each of these components and the methods of plating that are used are listed in Table IV.

The gold plating solutions that are actually used by the electronic plater may be conveniently classified by pH range: alkaline cyanide, pH >10; neutral cyanide, pH 6 to 9; acid cyanide, pH 3.5 to 5 (below pH 3.5 the gold cyanide is generally unstable and precipitates); noncyanide (usually sulfite), pH 9 to 10. Table V lists the baths that are primarily used by the industry.

Low-karat gold alloys [Group 2 or 3 (Class F)] have not found much application in the United States. The alloying metal generally affects the electrical properties of the gold

Table IV. Industrial/Electronic Gold Plating

				Plating Method		
	Purity	*Knoop Hardness No.*	*Surface*	*Rack*	*Barrel*	*Continuous*
Semiconductors	99.95%	60–80	Matte	Yes	Yes	Yes
Printed/etched circuits	99.5–99.7%	120–180	Bright	Yes	No	Yes
Contacts/connectors	99.5–99.7%	120–180	Bright	Yes	Yes	Yes

Gold Plating Technology

by F.H. Reid
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Table V. Electronic Gold Plating Solutions

	Alkaline Cyanide	*Neutral Cyanide*	*Acid Cyanide*	*Noncyanide*
Semiconductors	ClassD	ClassD	—	—
Printed circuits	—	—	ClassE	—
Connectors	Class E	—	ClassE	—

adversely. As little as 1% of iron will increase the electrical resistance of gold over 1,000%, and similar amounts of other metals have less, but still unacceptable, effects on the conductivity of the gold deposit. Even amounts of alloy much less than 1% will inhibit or totally prevent good welding or die bonding of semiconductor chips to a gold surface. Duplex coatings of a low-karat gold base overplated with a high-karat gold surface, although acceptable in some applications from an electrical point of view, have tended to lose their economic advantages as good engineering and new design have required less total gold.

ALKALINE CYANIDE BATHS (Group 1, Class D)

Table VI lists typical alkaline cyanide baths that are still used. Note that for matte deposits, the higher the temperature the better the deposit and the higher the speed of plating; however, temperatures over 150°F result in a rapid breakdown of the free cyanide and a buildup of cyanide breakdown impurities.

The alkaline cyanide baths are particularly sensitive to organic impurities, both those introduced by drag-in and by the absence of general cleanliness, as well as those caused by cyanide breakdown. To maintain a deposit that has a good appearance and is structurally sound it is necessary to carbon treat and filter the solution periodically. The grade of carbon used must be pure enough not to introduce more impurities than it removes. Constant filtration through a filter packed with carbon is accepted practice but is not as efficient in removing impurities as a batch treatment. If the solution is quite contaminated before treatment it is important to save the used carbon and the used filter cartridge for refining to recover any gold lost in the treatment.

The best method to carbon treat a solution is as follows: (1) Heat the solution to 150 to 160°F. (2) Transfer the hot solution to an auxiliary tank. (3) Add ⅛ to ¼ oz carbon per gallon of solution. (4) Mix for no longer than 20 to 30 min. (5) Filter the solution by decantation back into the original tank.

Table VI. Alkaline Cyanide Baths

	Matte	*Bright*
Gold as potassium gold cyanide (g/L)	8–20	8–20
Silver as potassium silver cyanide (g/L)	—	0.3–0.6
Dipotassium phosphate (g/L)	22–45	—
Potassium cyanide (g/L)	15–30	60–100
pH	12	12
Temperature (°F)	120–160	60–80
Anodes	Stainless steel	Stainless steel
Anode/cathode ratio	1:1	1:1–5:1
Agitation	Moderate to vigorous	None to moderate
Current density (A/ft^2)		
Rack	3–5	3–8
Barrel	1–2	1–2
Current efficiency (%)	90–95	90–100
Time to plate 0.0001 in.	8 min at 5 A/ft^2	7 min at 6 A/ft^2
Replenishment	1 oz gold/4½ A-hr	1 oz gold/4½ A-hr

Table VII. Neutral Cyanide Solutions

	Rack or Barrel Plating	*High-Speed Continuous Plating*
Gold as potassium gold cyanide (g/L)	8–20	15–30
Monopotassium phosphate (g/L)	80	—
or		
Potassium citrate (g/L)	70	90
pH	6.0–8.0	4.5–5.5
Temperature (°F)	160	120–160
Agitation	Desired	Violent
Anodes	Platinum-clad columbium	Platinum-clad columbium
Current density (A/ft^2)	1–3	100–400
Current efficiency (%)	90	95–98
Time to plate 0.0001 in.	12 min	10–20 sec
Replenishment	1 oz gold/4½ A-hr	1 oz gold/4½ A-hr

Table VIII. Acid Cyanide Plating Solutions

	Barrel Plating, Matte Bath 1	*Rack or Barrel Plating, Matte Bath 2*	*High-Speed Continuous Plating, Bright Bath 2*
Gold as potassium gold cyanide (g/L)	8	8	8–16
Citric acid (g/L)	60	60	90
Cobalt as cobalt metal (g/L)	—	0.2–0.5	0.75
or			
Nickel as nickel metal (g/L)			
pH	3.8–5.0	3.8–4.5	3.8–4.3
Temperature (°F)	120–140	70–90	70–120
Anodes	Platinum clad	Platinum clad or stainless steel	Platinum clad
Agitation	Desirable	Desirable	Violent
Current density (A/ft^2)	1–5	5–20	100–400
Current efficiency (%)		30–40	30–40
Time to plate 0.0001 in.		10 min at 10 A/ft^2	15 sec at 400 A/ft^2
Replenishment		1 oz gold/12 A-hr	1 oz gold/12 A-hr

No general rule can be given for the frequency of carbon treatment. This will depend on general cleanliness and housekeeping as well as the work being processed; however, it will vary from once every two weeks to once every two months. The room temperature bright bath will require much less carbon treatment than the hot cyanide bath.

NEUTRAL CYANIDE SOLUTIONS (Group 2, Class D)

The neutral cyanide baths are primarily used by the semiconductor industry. Considerable care must be exercised to prevent contamination of the solution because even a few parts per million of undesirable inorganics can cause the deposit to fail in compression or die bonding.

Typical nonproprietary solutions are listed in Table VII. Pulse plating may be used to advantage with the high-speed formulation. Most effective is a 10% duty cycle. Proprietary baths add grain refiners that decrease porosity, increase the maximum allowable current density, decrease grain size, and generally improve the appearance of the deposit.

ACID CYANIDE PLATING SOLUTIONS (Group 3, Class E)

Table VIII lists typical acid cyanide plating solutions. Note that pulse plating can be applied with the high-speed bath, but is not widely used.

INDIUM PLATING

by James A. Slattery

Indium Corp. of America, Utica, N.Y.

INDIUM CYANIDE BATH

Indium is the only trivalent metal that can readily be electrodeposited from a cyanide solution. Solution make-up and operational parameters are summarized in Table I. Indium hydroxide [$In(OH)_3$] is first prepared by the precipitation of indium chloride ($InCl_3$) using ammonium hydroxide or sodium hydroxide. The purified and dried $In(OH)_3$ is then dissolved in an alkaline cyanide solution stabilized with a sugar such as D-glucose, dextrose, or sorbitol. The cyanide bath is used in applications demanding extremely high throwing power and adhesion. Deposits are uniform and bright matte in appearance. Since this a high pH bath, it has the disadvantage of requiring the use of insoluble anodes, necessitating replenishment in the form of an indium cyanide concentrate. Its cathode efficiency is initially 90%, but upon bath aging decreases from this value to 50–75%. Periodic determination of the plating rate is thus required.

INDIUM SULFAMATE BATH

The indium sulfamate bath was developed to overcome several disadvantages of the cyanide bath. The sulfamate bath has the advantages of using soluble indium anodes and possesses a relatively constant cathode efficiency of 90%, which remains stable for the life of the bath. Sulfamate baths are very stable and are considered one of the easiest of all plating baths to operate and control. They even have a built-in pH indicator in that a milky white precipitate of indium hydroxide becomes evident if the pH should rise to >3.5. It is desirable,

Table I. Indium Cyanide Plating Bath

Indium as metal	4 troy oz/gal (33 g/L)
Dextrose	4 troy oz/gal (33 g/L)
Total cyanide (KCN)	12.77 oz/gal (96 g/L)
Potassium hydroxide (KOH)	8.5 oz/gal (64 g/L)
Temperature (static)	Room temperature
Cathode efficiency	50–75%
Anodes	Plain steel
Throwing power	Excellent
Quality of plate	Excellent
Ease of solution analysis	Difficult
Critical temperature (working)	None, with or without agitation
Color of solution	Clear, pale yellow to dark amber
Wettability	Easy
Tendency to pit	None
Control of solution	Cyanide and metal by additions
Use	General
Current	15–20 A/ft^2 (1.62–2.16 A/dm^2)

Replenishment: Since insoluble anodes are used, it is necessary to replace the indium metal content of this alkaline bath. A concentrate can be added directly to the bath. Under normal conditions, addition of cyanide will not be required; however, it is best to keep the cyanide concentration at ~100 g/L.

Efficiency: Plating efficiency of the bath will be maintained within a range suitable enough for normal plating until the indium content is reduced. Its plating rate should be checked at regular intervals because, as the bath is depleted, a decrease in rate of deposition is to be expected.

Table II. Indium Sulfamate Bath

Indium sulfamate	14 oz/gal (105.36 g/L)
Sodium sulfamate	20 oz/gal (150 g/L)
Sulfamic acid	3.5 oz/gal (26.4 g/L)
Sodium chloride	6 oz/gal (45.84 g/L)
Dextrose	1 oz/gal (8.0 g/L)
Triethanolamine	0.3 oz/gal (2.29 g/L)
pH[a]	1–3.5 (1.5–2 preferred)
Temperature (static)	Room temperature
Cathode efficiency	90%
Anode efficiency	100% with indium anodes
Throwing power	Excellent
Quality of plate	Excellent
Ease of solution analysis	Easy
Critical temperature (working)	None, with or without agitation
Color of solution	Clear (when new). After use will darken because of organic material breakdown. This has shown no effect on deposit. Filtering of bath can be done through activated carbon to maintain clarity of bath.
Wettability	Fairly easy
Tendency to pit	None
Control of solution	Metal and pH[a]
Use of solution	General
Current density	Optimum 10–20 A/ft^2 (1.08–2.16 A/m^2). If metal is increased, current density can be increased up to 100 a/ft^2 (10.8 A/dm^2)

[a] The pH of the bath is controlled by the addition of sulfamic acid.

however, to closely control pH preferably to 1.5–2.0. The pH tends to rise on operation and is lowered by the addition of granular sulfamic acid.

The bath possesses a throwing power only slightly less than the cyanide bath; deposits are uniform and bright matte in appearance. Operational parameters are summarized in Table II. One or more still water rinses incorporated after the plating tank will function as drag-out stations. Indium is easily recovered as $In(OH)_3$ by adjusting the pH to >5 with sodium hydroxide. The indium hydroxide formed is allowed to settle and then is collected so it can be shipped to refiners.

Table III. Indium Fluoborate Bath

Indium fluoborate	31.5 oz/gal (236 g/L)
Boric acid	2.9–4.0 oz/gal (22–30 g/L)
Ammonium fluoborate	5.3–6.7 oz/gal (40–50 g/L)
pH (colorimetric)	1.0
Temperature (static)	21–32°C (70–90°F)
Cathode efficiency	40–75%
Anode efficiency	100% with indium anodes
Throwing power	Good
Quality of plate	Good
Ease of solution analysis	Easy
Critical temperature (working)	21–32°C (70–90°F) with or without agitation
Color of solution	Clear
Wettability	Difficult
Tendency to pit	None
Control of solution	Metal and pH[a]
Use	General
Current density	50–100 A/ft^2(5.4–10.8 A/dm^2)

[a] The pH of this bath is controlled by the addition of 42% fluoboric acid. Some insoluble anodes (platinum or graphite) should be used, as the anode and cathode efficiency are not in good relation.

INDIUM FLUOBORATE BATH

The fluoborate bath offers the advantages of fine-grained deposits, ease of formulation from stable concentrates, and low fluctuations in bath composition. The pH is controlled by additions of fluoboric acid to the range 0.5–1.5. The bath uses pure indium anodes at 100% anode efficiency. The major drawback of this bath is the low cathode efficiency of 40–75%, which offsets advantages of plating at higher current density. A split anode system (indium and platinum) is usually employed to aid in equalizing the variances in the cathode and anode current efficiencies. Table III lists the operational parameters of the indium fluoborate bath.

COMPLEXED CHELATED ALKALINE BATHS

In the attempt to formulate a noncyanide alkaline bath employing soluble indium anodes, several baths have been proposed using EDTA, nitrilotriacetic acid, tartrates, and other chelating agents. Most have limitations in poor cathode efficiency and ease of recovery of spent plating solution and are not in widespread commercial use as compared with the sulfamate bath.

IRON PLATING

by Charles F. Lowrie

Van der Horst U.S.A. Corp., Terrell, Texas

Iron plating is very much alive, on a large scale, and doing exceptionally well even after almost one-half century of extremely heavy use and demand. The process is extremely complicated when performed in a manner designed to achieve desirable and functional metallurgical properties. Most of the common and widely publicized baths and related technology for producing electrolytic iron in mass quantity have been deserted for a simpler, but frequently (although not necessarily) better, alternative material and/or procedure. Most electrolytic iron is highly stressed and brittle and it, as well as the basis metal, is highly subject to hydrogen embrittlement. Its uses include: protecting soft or perishable metals and alloys such as copper and aluminum; reinforcing fragile metal forms; providing a surface for tinning; providing magnetic surfaces on nonmagnetic materials; as a reclamation technique; as an underlay for other metals; etc.

Most iron plating solutions are stable and simple to operate. The baths used include the chloride, sulfate, fluoborate, sulfamate, and also a proprietary solution developed by Hendrik and Kuno Van der Horst and their research staff, the Van der Horst bath. In a previous edition of this *Guidebook*, Roland H. Williams provided a knowledgeable, comprehensive, and informative review of the fundamental principles relating to the first four, and most common, baths mentioned above. His contribution certainly merits repeating. Any attempt to revise and/or rewrite the reference section of his article would be superfluous and thus it appears here basically unchanged.

SOLUTIONS AND OPERATING CONDITIONS

Chloride Bath

The most commonly used chloride bath is the ferrous chloride–calcium chloride solution. The deposits obtained from the chloride baths, if heat treated above 500°F, can be bent and formed a small amount. Most other solutions produce a deposit so brittle that it cannot be stressed without breaking. The chloride bath, however, presents containment and environmental problems because of the high temperature, toxicity, and acidity of the solution. The advantages of this bath are its high conductivity, high permissible current densities, fast plating rates, and relatively strong, ductile, smooth deposits. A typical bath is maintained as follows:

Ferrous chloride, dihydrate, 40–60 oz/gal
Calcium chloride, 20–25 oz/gal
Temperature, 190–210°F
Hydrochloric acid to pH 0.2–1.8
Current density, 20–80 A/ft^2 without agitation; to 200 A/ft^2 with agitation

Calcium chloride gives off heat in dissolving, so the water used should not be hot at the start. The solution is heated to >150°F and the pH lowered to ~0.8–1.0 with hydrochloric acid. Degreased steel wool is then added to reduce the ferric ion, along with activated carbon to remove harmful organic impurities. The solution is finally filtered into the plating tank, using a siliceous filter aid.

Maximum ductility is obtained at higher temperatures, lowest pH, and high current density. Heat treat at 500°F for 2 hr per ⅛ in. of thickness. Harder deposits are obtained at 190°F, $pH > 1.0$, and lower current densities.

Continuous addition of hydrochloric acid is recommended to control pH. High-purity iron anodes must be used if ductile deposits are derived because the solution is easily contaminated by carbon and alloying metal found in steels.

Sulfate Baths

Where plating speed is of no concern and lower operating temperatures are desired, the sulfate plating baths are suitable. The current density at which burning occurs is about one-half that of the chloride solutions. The sulfate is also not as soluble as the chloride. On the other hand, the sulfate solution can be operated at appreciably lower temperatures than can the chloride solution. For example, whereas the deposit stress becomes excessive below 190°F in the chloride solution, the stress of a deposit from a sulfate solution is not excessive at as low as 90°F if the current density is limited to 40 A/ft^2.

Ferrous Sulfate

Ferrous sulfate, 32 oz/gal
pH, 2.8–3.5
Temperature, 90–150°F
Current density, maximum of 40 A/ft^2 at 90°F; to 100 A/ft^2 at 150°F
Surface tension, 40 dynes/cm
Cathode agitation is desirable.

Ferrous Ammonium Sulfate

Ferrous ammonium sulfate, 33–48 oz/gal
pH, 2.8–5.0
Temperature, 75–150°F
Current density, 20 A/ft^2 at 75°F; to 100 A/ft^2 at 150°F
Cathode agitation is desirable.

Instead of ferrous ammonium sulfate, the bath can be prepared with 23–34 oz/gal ferrous sulfate ($FeSO_4 \cdot 7H_2O$) plus 11–16 oz/gal ammonium sulfate.

Mixed Sulfate–Chloride

Ferrous sulfate, 33 oz/gal
Ferrous chloride, 4.8 oz/gal
Ammonium chloride, 2.7 oz/gal
pH, 3.5–5.5
Temperature, 80–160°F
Current density, 20–100 A/ft^2
Cathode rod agitation.

Fluoborate Bath

The fluoborate bath, like other fluoborate solutions, received considerable impetus during the 1940s and early 1950s. The solution has a high conductivity and good stability. The claim is made for higher current densities than the chloride solution at lower operating temperatures. The bath, in general, is similar to the others. The current efficiency drops with decreasing pH, the deposit is made brittle and stressed by organic contamination, and increased operating temperatures permit higher metal content and higher current densities.

Iron fluoborate, 30.3 oz/gal
Metallic iron, 7.37 oz/gal
Sodium chloride, 1.34 oz/gal
Baumé at 80°F, 19–21°
pH (colorimetric), 3.0–3.4
Temperature, 135–145°F
Average tank voltage, 2–6 V
Average cathode current density, 20–90 A/ft^2
Anode/cathode ratio, 1:1.

Two thirds of the required amount of water is placed in the plating tank, and the specified amount of sodium chloride is added. When the salt has been completely dissolved, the ferrous fluoborate concentrate is added directly into the tank. Water is then added to bring the volume of the solution up to its required concentration. After this, the solution should be adjusted to the specified operating pH, clarified by treatment with activated carbon in a storage tank and then filtered. The carbon may be built up on the filter pads and the solution circulated through the filter, but sufficient time must be allowed to remove the solid particles and other contaminants. Electrolysis at 3–5 A/ft^2 is also recommended. The bath is then heated to operating temperature and is ready for use.

Sulfamate Bath

The sulfamate bath is similar to the sulfate bath but permits higher cathode current density. Iron sulfamate is available as a purified solution concentrate. The general characteristics of the deposit with respect to stress, hardness, and permissible current density are similar to those from other iron plating baths. Table I gives bath make-up and operating conditions.

Proprietary addition agents are available to reduce the stress and, as in other iron solutions, a wetting agent is recommended to eliminate pitting. In general, precautions against contamination and the usual purification procedures apply to this solution.

Van der Horst Bath

The Van der Horst bath is an extremely complicated solution. This bath and all of its operating conditions including, but not limited to, components, pH, temperature, and current density are strictly confidential and proprietary. When all of the necessary criteria are strategically orchestrated, the ultimate electroplate, which is characterized by dense, fine-grained, columnar, electrolytic, 99.9%-pure iron, is molecularly bonded to a wide variety of basis metals. The microstructure remarkably enables it to resist wear and coining; and the excellent adhesion to the basis metal ensures that the basis metal will generally fail prior to the deposit. Its tensile strength is ~95,000 psi, the yield point is >60,000 psi, and the average

Table I. Sulfamate Bath Make-Up and Operating Conditions

	Range	*Recommended*
Iron as ferrous ion, oz/gal	9–15	10
Ammonium sulfamate, oz/gal	3–6	4–5
Sodium chloride, oz/gal	3–8	5–6
pH	2.5–3.3	2.7–3.0
Temperature, °F	110–150	120–140
Current density, A/ft^2	10–100	50

hardness is 225 Brinell. Large mismachined or worn compressor, engine, and other parts are favorable candidates for reclamation with this process. It is utilized most frequently as an underlay for porous chromium or other specialty metal-finishing techniques but may also serve as a finished surface in those rare, but critical, applications where chromium is inappropriate.

Over the years, original equipment manufacturers (OEMs) have increasingly found it advantageous to salvage their costly investment in a nearly completed, but mismachined, component by placing their earned confidence in this electrolytic iron. Examples of such parts include compressor, power, and other cylinders, drums, turbine volutes and components, diesel engine, machine parts, etc. In many instances, the process actually improves the strength, durability, and/or performance of the virgin part.

As a reclamation technique, this unique process permits the restoration to service of worn cylinders from the natural gas and petrochemical industries and other parts, which would otherwise not be economically feasible. Due to the physical limitations inherent in chromium and other reclamation procedures related to relatively large oversizes, the process offers a high purity, homogenous base, which usually equals or exceeds the physicals of the basis metal, for chromium or some other surface finish. In certain applications, up to at least ½ in. of basis metal can be uniformly restored. Literally millions of parts utilizing this process have been in worldwide service for years and continue to be, and new applications are occurring every day.

A relatively recent major modification of the conventional Van der Horst bath has been produced. Although still in the developmental stage, preliminary results of laboratory tests have substantiated the vast potential of this material. The iron has already found its way into the test and production engines of a major OEM, as well as a large natural gas transmission plant. These companies are impressed with the results they are experiencing with their endeavor to reclaim their large worn power cylinders through an alternative means to chromium plating. Many other companies now using chromium or one of the other reclamation processes on the market are most eager to contribute their laboratory and/or production facilities for further study of the material. The deposit could, obviously, contribute to the reduction of the use of chromic acid used in the production of electrolytic chromium.

This new and revolutionary electrolytic iron involves a process that is environmentally safe since all chemicals used are either already nonhazardous or can be readily and easily rendered so. From an environmental standpoint, the process appears to be very attractive and sound. Although optimum physical characteristics are yet to be refined, the deposit will possess a hardness of 45–50 R_c, which is approaching that of hard chromium, a tensile strength of ~235,000 psi, and a sheer strength of >50,000 psi. A bond to a variety of basis metals has been perfected and is, in fact, molecular in nature. The surface of the material is made up of a network of channel-type porosity, which greatly enhances its lubricity. This bath produces a deposit that is independently functional and performs quite harmoniously when appropriately combined with its conventional counterpart.

NICKEL PLATING

by George A. DiBari

International Nickel Inc., Saddle Brook, N.J.

Nickel electroplating is one of the most versatile surface-finishing processes available having a broad spectrum of end uses that encompass decorative, engineering, and electroforming applications. Decorative coatings are obtained by electroplating from special solutions containing organic addition agents. The coatings are protective, mirror-bright, and smooth. Nickel coatings for engineering purposes are usually prepared from solutions that deposit pure nickel. The property sought in engineering end uses is generally corrosion resistance, but wear resistance, solderability, and magnetic and other properties may be relevant in specific applications. Electroforming is a specialized use of the electroplating process in which nickel is deposited and subsequently removed from a mandrel to yield an all-nickel component or article. Electroformed nickel products, such as molds, dies, record stampers, seamless belts, and textile printing screens are important commercial products. The processes used for decorative, engineering, and electroforming purposes are described below, after reviewing some basic facts about the nickel-plating process.

BASIC CONSIDERATIONS

Nickel plating is the electrolytic deposition of a layer of nickel on a substrate. The process involves the dissolution of one electrode (the anode) and the deposition of metallic nickel on the other electrode (the cathode). Direct current is applied between the anode (positive) and the cathode (negative). Conductivity between the electrodes is provided by an aqueous solution of nickel salts.

When nickel salts are dissolved in water, the nickel is present in solution as divalent, positively charged ions (Ni^{2+}). When current flows, divalent nickel ions react with two electrons ($2e^-$) and are converted to metallic nickel (Ni^0) at the cathode. The reverse occurs at the anode where metallic nickel dissolves to form divalent ions.

The electrochemical reaction in its simplest form is:

$$Ni2+ + 2e- = Ni0$$

Because the nickel ions discharged at the cathode are replenished by the nickel ions formed at the anode, the nickel plating process can be operated for long periods of time without interruption.

Estimating Nickel Thickness

The amount of nickel that is deposited at the cathode is determined by the product of the current (in amperes) and the time (in hours). Under ideal conditions, 26.8 A flowing for 1 hr will deposit 29.4 g of nickel (1.095 g/A-hr). If the area being plated is known, the average thickness of the nickel coating can be estimated. For example, if 29.4 g of nickel are deposited on 1 ft^2, the thickness of the deposit is 0.0014 in (Thickness equals the weight of nickel divided by the product of the area and the density of nickel. It is important to use consistent units. The density of nickel is 0.322 lb/in^3.)

Because a small percentage of the current is consumed at the cathode in discharging hydrogen ions, the efficiency of nickel deposition is less than 100%. This fact must be taken into account in estimating the weight and the thickness of nickel that will be deposited under practical plating conditions. Table I is a data sheet on depositing nickel based on 96.5%

Table I. Data Sheet on Depositing Nickel (Based on 96.5% Cathode Efficiency)

					Minutes for Obtaining Coating at Various Current Densities, A/ft^2			
Thickness, in.	*Thickness, μm*	*Oz/ft^2*	*G/ft^2*	*A-hr*	*10*	*20*	*50*	*100*
0.0001	2.5	0.0721	2.04	1.99	12	6	2.5	1.2
0.0002	5.1	0.144	4.08	3.98	24	12	5	2.4
0.0005	12.7	0.360	10.2	9.95	60	30	12	6
0.0008	20.3	0.578	16.3	15.9	96	48	19	9.6
0.0010	25.4	0.721	20.4	19.9	119	60	24	12
0.0015	38.1	1.082	30.6	29.8	179	89	36	18
0.0020	50.8	1.44	40.8	39.8	238	119	48	24

cathode efficiency. The table relates coating thickness, weight per unit area, current density, and time of plating. Some factors useful in making nickel-plating calculations are given in Table II.

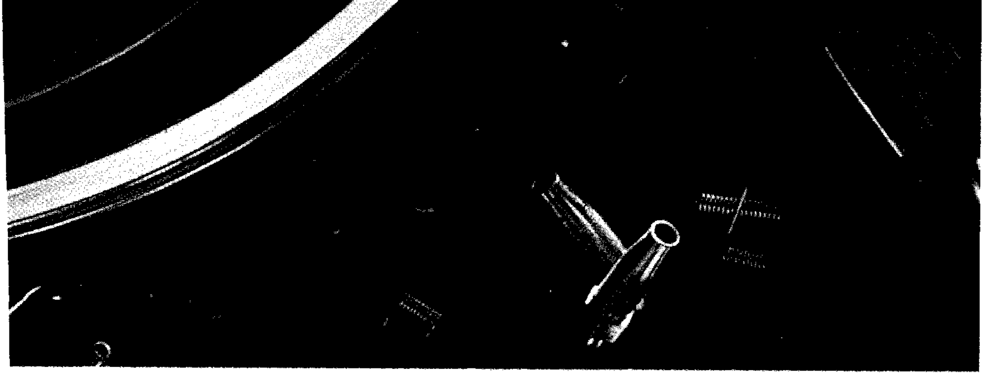
Anode efficiency is normally 100%. Because anode efficiency exceeds cathode efficiency by a small percentage, nickel-ion concentration and pH will rise as the bath is used. Drag-out of nickel-plating solution may compensate for nickel metal buildup in solution to some extent, but at some point if may be necessary to remove a portion of solution from the plating tank and replace the solution removed with water and other constituents. The pH of the solution is normally maintained by adding acid.

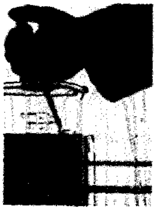
Metal Distribution

It is desirable to apply uniform thicknesses of nickel on all significant surfaces to achieve predictable service life and to meet plating specifications that require minimum coating thickness values at specified points on the surface. The amount of metal that deposits on the surface of any object being plated is proportional to the current that reaches the surface. Recessed areas on the surface receive less current. The current density and, consequently, the rate of metal deposition in the recessed area are lower than at points that project from the surface. The electrodeposited coating is relatively thin in recessed areas and relatively thick on projecting areas (Fig. 1).

Table II. Factors Useful in Making Nickel Plating Calculations (Assumes 100% Cathode Efficiency)

Multiply	*By*	*To Estimate*
Wt. of $NiSO_4 \cdot 7H_2O$	21%	Wt. of nickel contained
Wt. of $NiSO_4 \cdot 6H_2O$	22%	Wt. of nickel contained
Wt. of $NiCl_2 \cdot 6H_2O$	25%	Wt. of nickel contained
Wt. of $NiCl_2 \cdot 6H_2O$	30%	Wt. of chloride contained
Wt. of nickel carbonate	50%	Wt. of nickel contained
A-hr/ft^2 nickel plating	1.095	g nickel deposited
	0.0386	oz nickel deposited
A-min/ft^2	0.00086	mil of nickel deposited
Mil thickness	19.18	A-hr/ft^2
	1151	A-min/ft^2
	0.0226	g/cm^2
	0.742	oz/ft^2





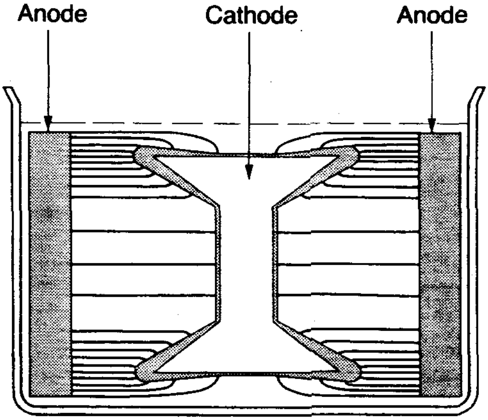


Fig. 1. Current distribution is not uniform over a shaped article. Areas remote from the anode receive a smaller share of the available current than areas near the anode.

The thickness of the deposit at the cathode and the distribution of the coating can be controlled by proper racking and placement of the parts in solution, and by the use of thieves, shields, and auxiliary anodes. Parts can be designed to minimize problems. It may be necessary to deposit more nickel than is specified to meet a minimum thickness requirement on a specific article.

The nickel processes used for decorative, engineering and electroforming purposes have the same electrochemical reaction. The weight of nickel deposited at the cathode is controlled by natural laws that make it possible to estimate the thickness of the nickel deposited. These estimates must be adjusted to account for variations in cathode efficiencies for specific processes. Normally, cathode efficiency values are between 93% and 97% for most nickel processes. Some of the so-called "fast" bright nickel-plating processes may have lower efficiencies. The actual thickness at any point on a shaped article depends on current flow. In practice, it is necessary to measure coating thickness on actual parts and make necessary adjustments to racks, thieves, and/or shields before thickness can be controlled within a specified range.

DECORATIVE NICKEL PLATING

The development of bright and semibright nickel-plating solutions, multilayer nickel coatings, and microporous and microcracked chromium have resulted in great improvements in the appearance and corrosion performance of decorative nickel coatings. Modern decorative nickel-chromium coatings are brilliant, highly leveled, and long-lasting.

Decorative Processes

The solutions used for decorative plating contain organic addition agents that modify the growth of the nickel deposit to produce fully bright, semibright, and satinlike surfaces. The basic constituents—nickel sulfate, nickel chloride, and boric acid—serve the same purposes as they do in the Watts solution (Table III).

Nickel sulfate is the principal source of nickel ions; nickel chloride improves anode dissolution and increases solution conductivity; boric acid helps to produce smoother, more ductile deposits. Anionic antipitting or wetting agents are required to reduce the pitting due to the clinging of hydrogen bubbles to the products being plated. Nonfoaming wetting agents that lower surface tension are available for air-agitated solutions.

Table III. Nickel Electroplating Solutions and Typical Properties of the Deposits

	Watts Nickel	*Conventional Sulfamate*	*Concentrated Sulfamate*
		Electrolyte Composition, g/L	
$NiSO_4 \cdot 6H_2O$	225 to 300		
$Ni(SO_3NH_2)_2 \cdot 4H_2O$		315 to 450	500 to 650
$NiCl_2 \cdot 6H_2O$	37 to 53	0 to 22	5 to 15
H_3BO_3	30 to 45	30 to 45	30 to 45
		Operating Conditions	
Temperature, °C	44 to 66	32 to 60	normally 60 or 70
Agitation	Air or mechanical	Air or mechanical	Air or mechanical
Current density, A/dm^2	3 to 11	0.5 to 32	Up to 90
Anodes	Nickel	Nickel	Nickel
pH	3.0 to 4.2	3.5 to 4.5	3.5 to 4.5
		Mechanical Properties	
Tensile strength, MPa	345 to 485	415 to 620	400 to 600
Elongation, %	15 to 25	10 to 25	10 to 25
Vickers hardness, 100 g load	130 to 200	170 to 230	150 to 250
Internal stress, MPa	125 to 185 (tensile)	0 to 55 (tensile)	See text.

The composition and operating conditions given in Table III for the Watts solution are typical of many decorative nickel-plating solutions, but wide variations in the concentrations of nickel sulfate and nickel chloride are possible. Since most decorative nickel-plating processes are proprietary, composition and operating conditions should be controlled within the limits recommended by the suppliers.

Bright Nickel Solutions

Bright nickel solutions contain at least two types of organic addition agents, which complement each other and yield fully bright nickel deposits.

One type produces deposits that are mirror-bright initially, but are unable to maintain the mirrorlike appearance of the deposit as its thickness is increased. This class includes compounds like benzene disulfonic acid, and benzene trisulfonic acid, benzene sulfonamide and sulfonimides such as saccharin. The presence of the sulfon group and an unsaturated bond adjacent to the sulfon are critical characteristics. Adsorption of the addition agent occurs by virtue of the unsaturated bond, onto growth sites, points or edges of crystals, and at dislocations. The organic compound is reduced electrochemically at the cathode, and this is accompanied by the reduction and incorporation of sulfur (as the sulfide) in the deposit. Fully bright nickel deposits typically contain 0.06% to 0.12% sulfur. These reactions control the structure and growth of the nickel as it is deposited.

The second type may be termed leveling agents because they make the surface smoother as the thickness of the deposit is increased. They are sulfur-free, bath-soluble organic compounds containing unsaturated groups and generally introduce small amounts of carbonaceous material into the deposit. Typical examples of this second of class brighteners are formaldehyde, coumarin, ethylene cyanohydrin, and butynediol.

The combination of organic addition agents makes it possible to obtain smooth, brilliant, lustrous deposits over wide ranges of current density. The deposits have a banded structure consisting of closely spaced laminations believed to be related to the co-deposition of sulfur. Certain cations, for example. zinc, selenium, and cadmium, enhance the luster of electrodeposited nickel, and have been used in combination with the organic additives. Supply houses provide instructions for proprietary bright nickel processes that specify rates of replenishment and methods of analyses for specific addition agents.

Semibright Nickel

Semibright nickel solutions contain nickel sulfate, nickel chloride, boric acid, and a leveling agent. The original process used coumarin as the principal additive. Coumarin-free processes are now available. The process yields deposits that are semilustrous. The deposits are smooth and have a columnar structure unlike the banded structure characteristic of fully bright deposits.

The solution was developed to facilitate polishing and buffing; semibright nickel deposits are easily polished to a mirror finish. Efforts to eliminate polishing led to the combination of semibright and bright nickel deposits. Experience has shown that a multilayer nickel coating has greater resistance to corrosion than a single-layer coating of equivalent thickness.

Single Layer and Multilayer Nickel Coatings

Single and multilayer nickel coatings are used to produce decorative coatings that resist corrosion. Single-layer bright nickel deposits are specified for mildly corrosive service. Double-layer coatings are specified for use in severe and very severe service. In double-layer coatings, the first nickel layer is deposited from a semibright bath. The second layer is then deposited from a bright bath. Triple-layer coatings may also be specified for severe and very severe service. In this case, a special thin layer of bright, high-sulfur nickel is deposited between the initial layer of semibright nickel and the top layer of bright nickel. The very thin layer should comprise about 10% of the total nickel coating thickness and must contain greater than 0.15% sulfur (as compared with 0.06% to 0.10% normally found in fully bright deposits).

Multilayer nickel coatings provide improved protection because the active, sulfur-bearing bright nickel layer protects the underlying sulfur-free layer by sacrificial action. For optimum corrosion performance, it is critical that the semibright nickel layer contain no codeposited sulfur.

Microdiscontinuous Chromium

Electrodeposited chromium is applied on top of the decorative multilayer nickel coatings to prevent tarnishing of the nickel when exposed to the atmosphere. The chromium coating is relatively thin compared with the nickel, because electrodeposited chromium is not intrinsically bright and will become dull if thickness is increased beyond an acceptable level. Studies of the corrosion performance of multilayer nickel plus *conventional* chromium coatings revealed a tendency to form one or two relatively large corrosion pits that would rapidly penetrate to the basis metal. This was believed to be due to the relatively low porosity of the top layer of chromium. It was concluded by many investigators that a pore-free chromium electrodeposit should improve corrosion resistance. The pore-free chromium plating processes developed in the early 1960s were short-lived when it was observed that the chromium layer did not remain pore-free in use.

Other investigators concluded that chromium deposits with high porosity or crack densities on a microscopic scale would be preferable. This led to the development of microdiscontinuous chromium deposits of two types: microporous and microcracked. These deposits greatly improve corrosion performance by distributing the available corrosion current over a myriad number of tiny cells on the surface of the coating. Corrosion proceeds uniformly over the entire surface instead of concentrating at one or two pits and, as a result, the rate of pit penetration is slowed dramatically. Double-layer nickel coatings 40 μm thick (1.5 mils) electroplated with either microporous or microcracked chromium and applied uniformly resisted corrosion in severe service for more than 16 years.

Specifying Decorative Nickel Coatings

The specification of decorative nickel coatings is often misunderstood, despite the availability of good technical standards (ASTM Standard B 456 and ISO Standard 1456) that

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Table IV. Requirements for Double- or Triple-Layer Coatings

Layer (type of Nickel Coating)	*Specific Elongation, (%)*	*Sulfur Content, (m/m)*	*Thickness (Percentage of Total Nickel Thickness)*	
			Double-Layer	*Triple-Layer*
Bottom (s)				
Middle (high-sulfur b)	—	Greater than 0.15	—	10
Top (b)	—	Greater than 0.04 and less than 0.15	Less than 40	Less than 40

provide the necessary guidance. Some of the requirements for double- or triple-layer nickel coatings are summarized in Table IV. These requirements specify the ductility (percent elongation) of the underlying semibright nickel layer, the sulfur content of each layer, and the thickness of each layer as a percentage of the total nickel thickness. For example, for double-layer nickel coatings on steel, the semibright nickel layer should be 60% of the total nickel thickness. This ratio is important for controlling the corrosion performance, the ductility and the cost of the double-layer coating (the semibright nickel process is generally less expensive than the bright nickel one).

In addition to these general requirements, the standards give recommended thicknesses for nickel plus chromium coatings for various service conditions. The recommendations for coatings on steel from ASTM Standard B 456 are reproduced in Table V. The service condition number characterizes the severity of the corrosion environment: 5 being the most severe and 1 being the least severe. The classification numbers given in the second column of the table specify the coatings that are expected to meet the requirements of the condition of service.

For example, the classification number: *Fe/Ni35d Cr mp* indicates that the coating is suitable for very severe service; it is applied to steel (Fe); the double-layer (d) nickel coating is 35 μm thick and has a top layer of microporous (mp) chromium that is 0.3 μm thick. (The thickness of the chromium is not included unless it differs from 0.3 μm.)

The type of nickel is designated by the following symbols: b, for electrodeposited bright nickel (single-layer); d, for double or multilayer nickel coatings; p, for dull, satin, or semibright unpolished nickel deposits; s, for polished dull or semibright electrodeposited

Table V. Nickel Plus Chromium Coatings on Steel

Service Condition Number	*Classification Number* [a]	*Nickel Thickness, Micrometers (mil)*
SC 5 (extended time, very severe)	Fe/Ni35d Cr mc	35 (1.4)
	Fe/Ni35d Cr mp	35 (1.4)
SC 4 (very severe)	Fe/Ni40d Cr r	40 (1.6)
	Fe/Ni30d Cr mc	30 (1.2)
	Fe/Ni30d Cr mp	30 (1.2)
SC 3 (severe)	Fe/Ni30d Cr r	30 (1.2)
	Fe/Ni25d Cr mc	25 (1.0)
	Fe/Ni25d Cr mp	25 (1.0)
	Fe/Ni40p Cr r	40 (1.6)
	Fe/Ni30p Cr mc	30 (1.2)
	Fe/Ni30p Cr mp	30 (1.2)
SC 2 (moderate)	Fe/Ni20b Cr r	20 (0.8)
	Fe/Ni15b Cr mc	15 (0.6)
	Fe/Ni15b Cr mp	15 (0.6)
SC 1 (mild)	Fe/Ni10b Cr r	10 (0.4)

[a] See text for explanation of Classification Numbers.

nickel. The type of chromium is given by the following symbols: r, for regular or conventional chromium; mp, for microporous chromium; mc, for microcracked chromium.

The standards provide additional information to assure the quality of electrodeposited decorative nickel-plus-chromium coatings. In essence, the available standards, which summarize many years of corrosion experience, show that multilayer nickel coatings are significantly more corrosion resistant than single-layer bright nickel coatings. Microdiscontinuous chromium coatings provide more protection than conventional chromium, and the corrosion protection afforded by the use of decorative electroplated nickel-plus-chromium coatings is directly proportional to the thickness of the nickel.

"Total quality improvement" goals cannot be achieved without understanding and complying with the requirements contained in technically valid standards.

ENGINEERING NICKEL PLATING

Engineering or industrial applications for electrodeposited nickel exist because of the useful properties of the metal. Nickel coatings are used in these applications to modify or improve surface properties, such as corrosion resistance, hardness, wear, and magnetic characteristics. Although the appearance of the coatings is important and the plated surface should be defect-free, the lustrous, mirrorlike deposits described in the preceding section are not required.

Engineering Plating Processes

Typical compositions and operating conditions for electrolytes suitable for engineering applications have been included in Table III. In addition, electrolytes for industrial plating, including all-chloride, sulfate-chloride, hard nickel, fluoborate, and nickel-cobalt alloy plating have been discussed by Brown and Knapp.[1]

Mechanical Properties

The mechanical properties are influenced by the chemical composition and the operation of the plating bath as indicated in Table III. The tensile strength of electrodeposited nickel can be varied from 410 to 1,170 MPa (60 to 170 psi) and the hardness from 150 to 470 DPN by varying the electrolyte and the operating conditions.

The operating conditions significantly influence the mechanical properties of electrodeposited nickel. Figures 2, 3, and 4 show the influence of pH, current density, and temperature on the properties of nickel deposited from a Watts bath. Additional information on how the properties of electrodeposited nickel are controlled is available.[2]

The mechanical properties of electrodeposited nickel vary with the temperature to which the coatings are exposed as shown in Figure 5. The tensile strength, yield strength and ductility of electrodeposited nickel reaches low values above 480°C (900°F). Nickel deposits from sulfamate solutions are stronger at cryogenic temperatures than deposits from the Watts bath.

Corrosion Resistance

Engineering nickel coatings are frequently applied in the chemical, petroleum, and food and beverage industries to prevent corrosion, maintain product purity, and prevent contamination. As a general rule, oxidizing conditions favor corrosion of nickel in chemical solutions, whereas reducing conditions retard corrosion. Nickel also has the ability to protect itself against certain forms of attack by developing a passive oxide film. When an oxide film forms and is locally destroyed as in some hot chloride solutions, nickel may form pits. In general, nickel is resistant to neutral and alkaline solutions, but not to most of the mineral acids.

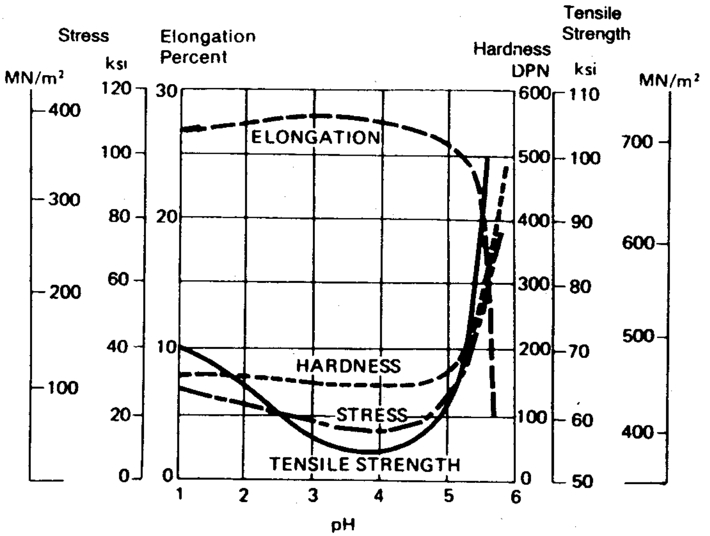

Fig. 2. Variation in internal stress, tensile strength, ductility, and hardness with pH. Watts bath 54°C (130°F) and 495 A/m² (46 A/ft²).

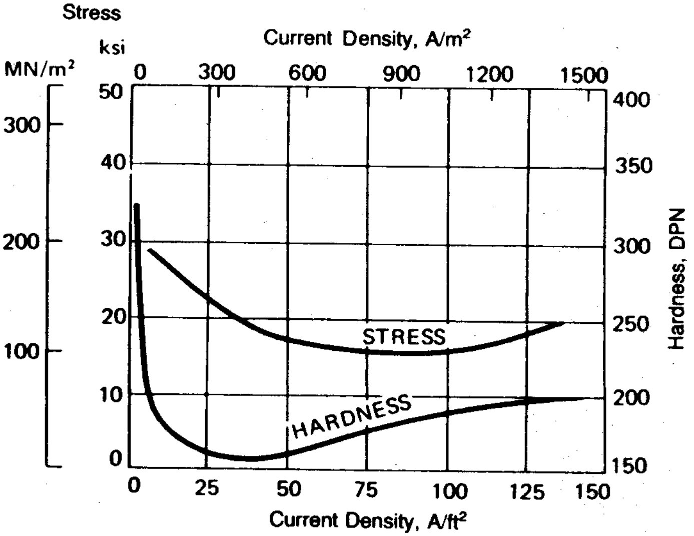

Fig. 3. Variation in internal stress and hardness with current density. Watts bath 54°C (130°F) and pH 3.

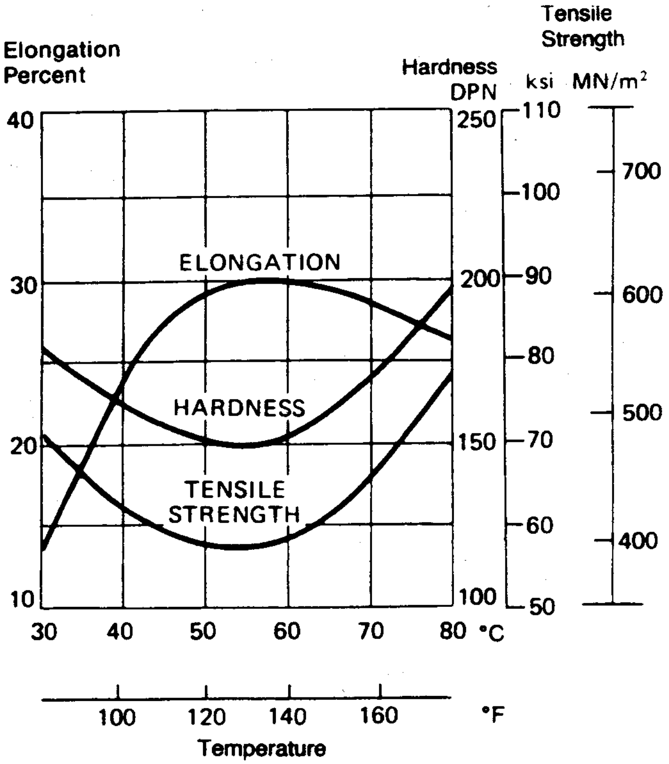

Fig. 4. Variation in elongation, tensile strength, and hardness with temperature. Watts bath pH 3 and 495 A/m² (46 A/ft²).

Corrosion resistance in engineering applications is controlled by optimizing nickel thickness. The thickness of the nickel is dependent on the severity of the corrosive environment. The more corrosive the service conditions the greater the thickness of nickel required. Thickness generally exceeds 0.003 in. (75 μm) in engineering applications.

Nickel Plating and Fatigue Life

Thick nickel deposits applied to steel may cause significant reductions in the composite fatigue strength in cyclical stress loading. The reduction in fatigue strength is influenced by the hardness and strength of the steel and the thickness and internal stress of the deposits. Lowering the internal stress of the deposits lowers the degree of reduction in fatigue life; compressively stressed nickel deposits are beneficial. Fatigue life is enhanced by increasing the hardness and strength of the steel and by specifying the minimum deposit thickness consistent with design criteria. Shot peening the steel prior to plating helps minimize reduction in fatigue life upon cyclical stress loading.

Hydrogen Embrittlement

Highly stressed, high-strength steels are susceptible to hydrogen embrittlement during normal plating operations. Because nickel plating is highly efficient, hydrogen damage is

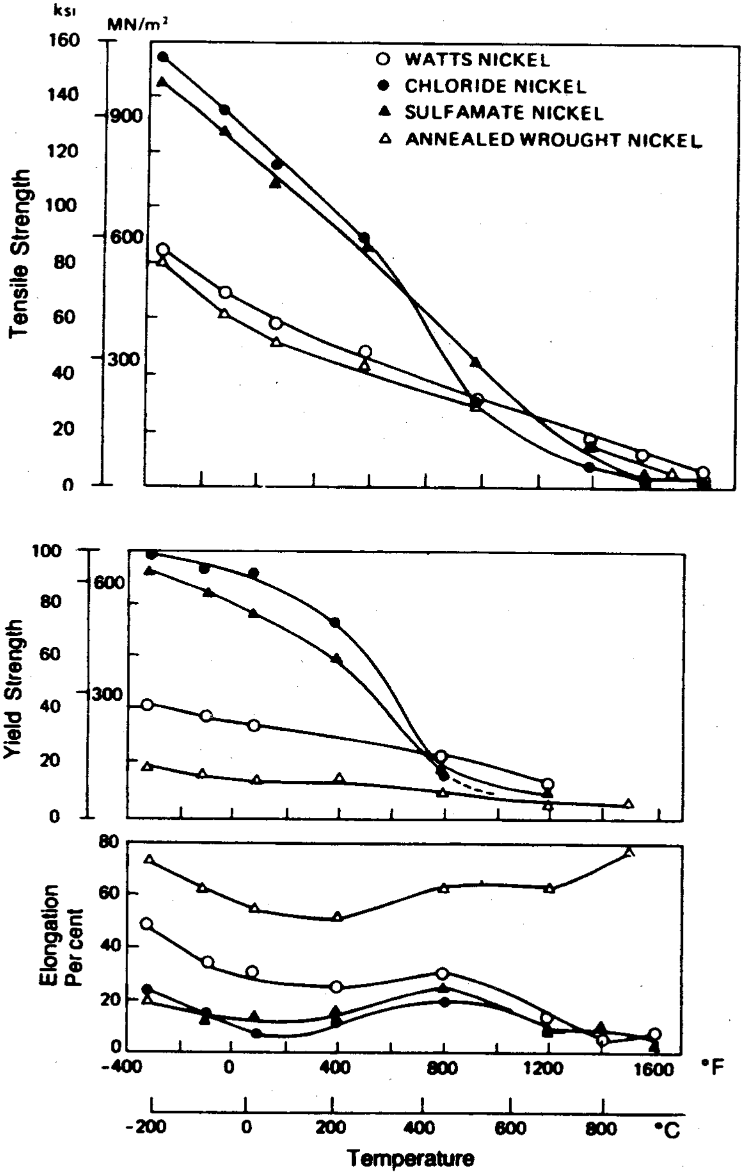

Fig. 5. Effect of temperature on the tensile strength, yield strength, and elongation of electrodeposited nickel.

Table VI. Relationship between Temperature, Current Density, and Plating Rate for Zero Stress Deposits from the Concentrated Nickel Sulfamate Solution Described in the Text

Temperature, (°C)	*35*	*40*	*45*	*50*	*55*	*60*	*65*	*70*
Current density								
A/dm^2	1.1	2.7	4.3	8.1	13.5	17.8	21.6	32
A/ft^2	10	25	40	75	125	165	200	300
Plating rate								
µm/hr	12	31	50	94	156	206	250	375
mil/hr	0.5	1.2	2	3.7	6.2	8.2	10	15

unlikely to occur as a result of nickel plating *per se*. The pretreatment of steel prior to plating, however, may require exposing the steel to acids and alkalies. During these operations, excessive amounts of hydrogen may evolve which may damage steels susceptible to hydrogen embrittlement. Steels that are susceptible to hydrogen embrittlement should be heat treated to remove hydrogen. The time required may vary from 8 to 24 hr depending on the type of steel and the amount of hydrogen to be removed. The temperature is of the order of 205°C (400°F), and the exact temperature may be alloy dependent.

NICKEL ELECTROFORMING

Nickel electroforming is electrodeposition applied to the production of metal products. It involves the production or reproduction of products by electroplating onto a mandrel that is subsequently separated from the deposit. It is an extremely useful technology that continues to grow in importance.

Conventional Processes

The composition, operating conditions, and mechanical properties of deposits from the electrolytes most often used for electroforming (Watts nickel and conventional sulfamate) are given in Table III. Nickel sulfamate solutions are the most popular because the deposits are low in stress, high rates of deposition are possible, and the thickness of the deposit is less affected by variations in current densities than are deposits from Watts solutions. By maintaining the solution as pure as possible and the chloride as low as possible, the internal stress of the nickel sulfamate deposits can be kept close to zero. Watts solutions are very economical.

High-Speed, Low-Stress Process

A concentrated nickel sulfamate solution has been recommended for electroforming at high rates and at low stress levels in deposits that do not use organic stress reducers, which would introduce sulfur. The solution has a nickel sulfamate concentration of 550 to 650 g/L, a nickel chloride concentration of 5 to 15 g/L, and a boric acid concentration of 30 to 40 g/L. It is operated at a pH of 4.0, a temperature of 140 to 160°F (60 to 71°C) and at current densities as high as 800 A/ft^2. The high rates of plating are made possible by the high nickel concentration. When the bath is properly conditioned and operated, it is possible to control internal stress at or close to zero because of the interrelations of stress, current density, and solution temperature (Table VI).

After purification with carbon to remove all organic contaminants, the concentrated solution is given a preliminary electrolytic conditioning treatment consisting of (1) electrolysis at 0.5 A/dm^2 on both anode and cathode for up to 10 A-hr/L; (2) electrolysis at 0.5 A/dm^2 on the anode and at 4.0 A/dm^2 on the cathode for up to 30 A-hr/L of solution. For this conditioning treatment, the anode must be nonactivated (sulfur-free). A corrugated steel sheet may be used as the cathode. When the solution has been conditioned, a deposit at a current density of 5 A/dm^2 and at 60°C should be lustrous and the internal stress as determined with a spiral contractometer or other device should be 48 ± 14 MPa (7,000 ± 2,000 psi) compressive.

To control the internal stress and other properties during operation, the solution is electrolyzed continuously at low current density by circulating through a small, separate conditioning tank. The conditioning tank should have 10 to 20% of the capacity of the main tank and the total solution should be circulated through it two to five times per hour. For this to work, the anodes in the conditioning tank must be nonactive, whereas the anode materials in the main tank must be fully active (containing sulfur). This is a means of controlling the anode potential in the conditioning tank so that only a stress reducer that does not increase the sulfur content of the nickel is produced. The use of an active anode material in the main tank prevents formation of sulfamate oxidation products in that part of the system.

Zero-stress conditions can be obtained at the temperature and current density values given in Table VI. The plating rate is also indicated in the table. For example, at 50°C, the stress is zero at approximately 8 A/dm^2, and will become compressive below and tensile above that value. To deposit nickel at 32 A/dm^2 at zero stress, the temperature must be raised to 70°C. Despite its seeming complexity, this process is being used successfully to electroform stampers for compact disc manufacture where flatness of the stamper is critical and to electroform ultrathin nickel foil continuously on rotating drums.

The internal stress in deposits from sulfamate solutions is influenced by reactions at the nickel anode. When a nickel anode dissolves at relatively high potentials, stress reducers are produced by anodic oxidation of the sulfamate anion. The use of pure nickel in the conditioning tank and active nickel in the main tank is designed to control the nature and amount of the stress reducer formed in this high-speed bath.

QUALITY CONTROL

Improvement in total quality is required by all industrial activity, including nickel plating. Quality assurance involves maintaining the purity of the nickel-plating solution and controlling the properties of the deposits. Some of the control procedures are summarized here.

Purification of Solutions

Nickel-plating baths freshly prepared from technical salts contain organic and inorganic impurities that must be removed before the bath is operated. Older baths gradually become contaminated from drag-over from preceding treatments, from components that are allowed to fall off the rack and allowed to remain in the tank, from corrosion products from auxiliary equipment, from tools dropped into the tank, and from other sources. It is more effective to keep impurities out of the plating bath than to deal with rejects and production interruptions resulting from the use of impure solutions.

The maximum concentrations of impurities normally permissible in nickel plating solutions and recommended treatments for their removal are shown in Table VII. The electrolytic treatment referred to in the table, known as "dummying," involves placing a large corrugated cathode in the solution and plating at low current densities, 2 and 5 A/ft^2. Copper, lead, and certain sulfur-bearing organic addition agents are best removed at 2 A/ft^2, whereas iron and zinc are more effectively removed at 5 A/ft^2. A corrugated cathode is preferred because it gives a wider current density range. At 2 A/ft^2, impurities should be removed after the solution has been operated for 2 A-hr/gal; at 5 A/ft^2, 5 A-hr/gal should be sufficient.

The high pH treatment requires transferring the nickel solution to an auxiliary treatment tank. Sufficient nickel carbonate is added to bring the pH above 5.2. Approximately 0.5 to 1.0

Table VII. Maximum Concentration of Impurities and Purification Treatments

Impurity	*Maximum Conc. (ppm)*	*Purification Treatment*
Iron	50	High pH and electrolysis
Copper	40	High pH and electrolysis
Zinc	50	High pH and electrolysis
Lead	2	Electrolysis
Chromium	10 (hexavalent)	High pH. It may be necessary to precede this with a potassium permanganate-lead carbonate treatment, follwed by lead removal
Aluminum	60	High pH
Organic impurities	solution related	Activated carbon; activated carbon plus elecrolysis

ml/L of 30% hydrogen peroxide is added. The bath is agitated and kept warm for 2 hr. The pH is adjusted to the optimum level after the bath is filtered back into the main plating tank. The solution may then be electrolyzed at low current density until deposit quality is acceptable.

When organic impurities are to be removed, activated carbon is added prior to the high pH treatment described above. Approximately 0.13 to 0.4 oz/gal (1 to 3 g/L) of activated carbon is commonly added to the solution in the auxiliary treatment tank. The nickel carbonate and hydrogen peroxide are then added. The solution is then filtered. Electrolytic purification is often desirable at this point. After a new bath has been prepared, the high pH treatment, treatment with activated carbon, and electrolysis at low current densities are performed sequentially until the quality of the deposit as determined by the tests discussed in the next section is acceptable.

CONTROLLING THE PROPERTIES OF NICKEL DEPOSITS

Methods that measure thickness, adhesion, and corrosion resistance of nickel coatings are available as means of quality control. Properties such as porosity, ductility, tensile strength, internal stress, hardness, and wear resistance are important to control the quality of electroplated articles. Some of these properties may be measured by the following methods.

Thickness

Micrometer readings are often used to determine the thickness of a coating at a particular point when the deposit thickness exceeds 125 μm (0.005 in.). Other methods for determining the thickness of electrodeposited coatings can be found in ASTM standards. ASTM standard B 487 describes a method based on metallographic examination of cross-sections of the plated object. Alternate tests involve magnetic (ASTM B 530) and coulometric (ASTM B 504) measurements of thickness.

The STEP Test

The simultaneous thickness and electrochemical potential (STEP) test is similar to the coulometric method of determining thickness. By including a reference electrode in the circuit, however, it is possible to measure the electrochemical potential of the material being dissolved. The test was developed to control the quality of multilayer nickel coatings. For example, with double-layer nickel coatings, a large change in potential occurs when the bright nickel layer has dissolved and the underlying semibright nickel begins to be attacked. The potential difference is related to the overall corrosion resistance of the multilayer coating. The test has been standardized (ASTM B 764) and is specified for automotive plating.

Corrosion and Porosity Testing

Examination of the coated part after immersion in hot water for 2 to 5 hr for rust is one technique used in studying the corrosion resistance of plated steel. The number of rust spots in a given area is then used as the qualification for accepting or rejecting the piece. Modifications of this test include immersion for up to 5 hr in distilled water, in distilled water saturated with carbon dioxide, or in distilled water containing 0.5% by weight of sodium chloride at test temperatures of 82 to 85°C (180 to 185°F).

Several salt spray tests have been used to simulate marine environments. These tests are commonly used to evaluate nickel and nickel-plus-chromium coatings on ferrous and nonferrous substrates. The salt spray tests are also used as accelerated quality control tests and are described in the following standards: salt spray (ASTM B 117); acetic acid-salt spray (ASTM B 267); and copper-accelerated acetic acid-salt spray (CASS Test: ASTM B 368).

The ferroxyl test is another porosity test that is employed for coatings on ferrous metal substrates and involves the formation of Prussian blue color within exposed pits. The solution utilizes sodium chloride and potassium ferricyanide as reagents to develop the color.

The only truly satisfactory method of establishing the relative performance of various coating systems is by service testing. Therefore, care should be exercised in interpreting the results of accelerated corrosion tests. Once an acceptable service life has been determined for a specific thickness and type of coating, the performance of other candidate coatings may be compared against it.

Hardness

Hardness measurements involve making an indentation on the surface (or cross section for thin coatings) of the deposit. The indenter has a specified geometry and is applied with a specified load. In the case of industrial nickel coatings, the most common hardness determination is the Vickers method of forcing a diamond point into the surface under a predetermined load (normally 100 g). This provides a measure of that surface to permanent deformation under load. The figure obtained is not necessarily related to the frictional properties of the material nor to its resistance to wear or abrasion. The measurement of microhardness of plated coatings is discussed in ASTM B 578.

Internal Stress

The magnitude of internal stress obtained in deposits is determined by plating onto one side of a thin strip of basis metal and measuring the force causing the strip to bend. One method used in commercial practice involves plating the exterior surface of a helically wound strip and measuring the resultant change of curvature. Another method is based on the flexure of a thin metal disc. See ASTM B 636 for the method of measuring internal stress with the spiral contractometer.

Ductility

Most of the tests that have been used for evaluating the ductility of plated coatings are qualitative in nature. Two bend tests are described in ASTM B 489 and B 490. Both of these procedures require a minimum amount of equipment. Another method for measuring the ductility of thick deposits is to determine the elongation of a specimen in a tensile testing machine. This method is limited to relatively thick foils of controlled geometry and thickness. A method specifically designed for plated thin foils has been used and is known as the hydraulic bulge test. A mechanical bulge test is also available.

Adhesion

In general, the adhesion between a nickel coating and the basis material should exceed the tensile strength of the weaker material. As a result, when a force is applied to a test

Table VIII. Summary of Conditioning Steps in the Preparation of Metals for Plating[a]

	Conditioning Step One		*Conditioning Step Two*	
Basis Metal	*Solution*	*Operation*	*Solution*	*Operation*
Aluminum alloys	Zincate or stannate	Immersion	Copper cyanide strike	Deposit copper at 2.5 A/dm^2 for 2 min; then, at 1.3 A/dm^2 for 6 min
Copper alloys	Sulfuric or hydrochloric acid	Immersion		
Iron castings	Sulfuric or hydrochloric acid	Immerse and water rinse	Alkaline clean	At 6.5 to 10 A/dm^2, anodic
Lead alloys	10% Fluoborate	Immerse 10 to 15 sec		
Nickel	Acid nickel chloride	30 A/dm^2; anodic for 2 min; then cathodic for 6 min		
Stainless steels	65% Sulfuric acid	Cathodic for 2 min	Acid nickel chloride	Cathodic for 2 min at 16 A/dm^2
Low carbon steels	Alkaline cleaner	Anodic at 6 V for 1 to 2 min	10% Sulfuric acid	Immerse for 5 to 15 sec
High carbon steels	Sodium cyanide	Immerse or short anodic treatment	Sulfuric acid plus sodium sulfate solution	Anodic at 10 to 40 A/dm^2
Zinc	Copper cyanide	Cathodic strike	Cyanide copper	Cathodic

[a] This table only gives the final conditioning steps. These steps are preceded by other critical steps. For complete details see the section on Chemical Surface Preparation in this *Guidebook* and the *Annual Book of ASTM Standards*, volume 02.05, published by American Society for Testing and Materials, Philadelphia. Details are given in other handbooks including *Inco Guide to Nickel Plating*, available on request from Inco, Saddle Brook, N.J. 07662. Rinsing steps have not been included; in general, rinsing or double rinsing is beneficial after each conditioning step.

specimen, which tends to pull the coating away from the basis metal, separation occurs within the weaker material rather than at the boundary between the basis metal and the nickel coating. A number of qualitative tests have been used that utilize various forces applied in a multitude of directions to the composite basis metal and coating, such as hammering, filing, grinding, and deforming. Quantitative tests have also been described in the literature. Achieving good adhesion requires a sound bond between the substrate and the coating. A sound metallurgical bond may be achieved on most materials by proper surface preparation prior to plating. The selection of grinding, polishing, pickling and conditioning treatments for a variety of basis metals varies from one material to another, and depends on the initial surface condition of the metal. The activating treatments that follow polishing and cleaning operations are listed in Table VIII for the most commonly plated basis metals. ASTM standards provide additional information. Nonconductive plastics and other materials can be plated by metallizing the material, using etching and catalyzing techniques (ASTM B 727).

NICKEL ANODE MATERIALS

Important developments in nickel anode materials and their utilization have taken place. Of utmost significance was the introduction of titanium anode baskets in the 1960s. Today the use of expanded or perforated titanium anode baskets filled with nickel of a selected size has become the preferred method of nickel plating. Titanium anode baskets are preferred because they offer the plater a number of advantages. Primary forms of nickel can be used that provide the least costly nickel ion source. Anode replenishment is simple and can be automated. The constant anode area achieved by keeping baskets filled improves current distribution and conserves nickel.

Several forms of primary nickel are currently being used in baskets. These include electrolytic nickel squares or rectangles and button-shaped material that contains a small, controlled amount of sulfur. Nickel pellets produced by a gas-refining process and similar pellets containing a controlled amount of sulfur are being utilized.

Prior to the introduction of titanium anode baskets, wrought and cast nickel anode materials were the norm. They are still used, but not to the extent they were before 1960. The wrought and cast anode materials comprise rolled bars containing approximately 0.15% oxygen; rolled nickel containing approximately 0.20% carbon and 0.25% silicon; and cast bars containing approximately 0.25% carbon and 0.25% silicon. Soluble auxiliary anodes are generally carbon- and silicon-bearing small-diameter rods.

With the exception of the sulfur-bearing materials, nickel anodes require the presence of chloride ion in the plating bath to dissolve efficiently. Rolled or cast carbon-bearing materials are used up to a pH of 4.5, and oxygen-bearing, rolled depolarized anode bars can be used above a pH of 4.5 when chlorides are present in solution.

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PALLADIUM AND PALLADIUM-NICKEL ALLOY PLATING

by Ronald J. Morrissey

Technic Inc., Providence, R.I.

Palladium has been electroplated from a wide variety of systems, which can be broadly characterized as ammoniacal, chelated, or acid processes. Of these, the most numerous are the ammoniacal systems, in which palladium is present as an ammine complex, such as palladosamine chloride, $Pd(NH_3)_4Cl_2$, or diaminodinitrite, $Pd(NH_3)_2(NO_2)_2$, which is known popularly as the P-salt. Some representative formulations are shown as follows:

P-SALT/SULFAMATE

Palladium as $Pd(NH_3)_2(NO_2)_2$, 10–20 g/L
Ammonium sulfamate, 100 g/L
Ammonium hydroxide to pH 7.5–8.5
Temperature, 25–35°C
Current density, 0.1–2.0 A/dm^2
Anodes, platinized

PALLADOSAMINE CHLORIDE

Palladium as $Pd(NH_3)_4Cl_2$, 10–20 gL
Ammonium chloride, 60–90 g/L
Ammonium hydroxide to pH 8.0–9.5
Temperature, 25–50°C
Current density, 0.1–2.5 A/dm^2

Palladium electrodeposits are notably susceptible to microcracking induced by codeposition of hydrogen. For this reason, it is important to plate at current efficiencies as high as possible. Proprietary brightening and surfactant systems are available, which increase the range of current densities over which sound deposits may be obtained. Ammoniacal electrolytes, particularly at higher temperature and pH, tend to tarnish copper and copper alloys. Proprietary palladium strike solutions have been developed. In most cases, however, a nickel strike is sufficient.

Chelated palladium plating solutions contain palladium in the form of an organometallic complex. These solutions operate in the pH range of 5 to 7 and are in almost all cases proprietary. Requisite details may be obtained from the manufacturers.

Acid palladium plating solutions have been used for producing heavy deposits of very low stress. Such systems are ordinarily based on the chloride, although a proprietary sulfate solution brightened with sulfite has been reported. A representative formulation for the chloride systems is as follows:

ACID CHLORIDE

Palladium as $PdCl_2$, 50 g/L
Ammonium chloride, 30 g/L
Hydrochloric acid to pH 0.1–0.5
Temperature, 40–50°C

Current density, 0.1–1.0 A/dm^2
Anodes, pure palladium

Deposits from the acid chloride system are dull to semibright. Current efficiency is 97 to 100%. The plating solution itself is notably sensitive to contamination by copper, which can displace palladium from solution. Work to be plated in this solution should thus be struck with palladium or with gold.

PALLADIUM-NICKEL PLATING

Palladium readily forms alloys with other metals and has been plated in numerous alloy formulations. Of these, the most important commercially has been palladium-nickel, which can be deposited as a homogeneous alloy over a composition range from approximately 30% to over 90% palladium by weight. Current practice favors an alloy composition from approximately 75 to 85% wt. palladium. A formulation suitable for alloys in this range is as follows:

Palladium as $Pd(NH_3)_4Cl_2$, 18–28 g/L (palladium metal, 8–12 g/L),
Ammonium chloride, 60 g/L
Nickel chloride concentrate, 45–70 ml/L (nickel metal 8–12 g/L)
Ammonium hydroxide to pH 7.5–9.0
Temperature, 30–45°C
Current density, 0.1–2.5 A/dm^2
Anodes, platinized

Palladium-nickel alloy electrodeposits are notably less sensitive to hydrogen-induced cracking than are pure palladium deposits. They are, however, somewhat more susceptible than pure palladium to stress cracking upon deformation. As with pure palladium plating systems, various proprietary additives are available for brightening and stress control.

PLATINUM PLATING

by Ronald J. Morrissey

Technic Inc., Providence, R.I.

Electroplating solutions for the deposition of platinum are generally similar to those employed for palladium; however, whereas palladium ions in solution are almost always divalent, platinum ions exhibit stable valences of 2+ or 4+. Divalent platinum ions can become oxidized to quadrivalent at the anode, particularly in alkaline solution. Such oxidation can lead to progressive, sometimes erratic, losses in current efficiency. For this reason it is often useful to separate the anode compartment in electroplating solutions of this type.

Dinitroplatinite Sulfate, Sulfuric Acid

For plating platinum directly onto titanium for fabricating anodes the dinitroplatinite sulfate formulation has been employed:

Platinum as $H_2Pt(NO_2)_2SO_4$, 5g/L
Sulfuric acid to pH 2
Temperature, 40°C
Current density, 0.1–1 A/dm^2
Anodes, platinum

Chloroplatinic acid

An alternative acid formulation is based on chloroplatinic acid:

Platinum as H_2PtCl_6, 20 g/L
Hydrochloric acid, 300 g/L
Temperature, 65°C
Current density, 0.1–2 A/dm^2
Anodes, platinum

Chloroplatinic Acid, Ammoniacal

In chloroplatinic acid platinum ions are quadrivalent rather than divalent, as in the dinitroplatinite sulfate. Plating formulations based on chloroplatinic acid can also be operated at neutral to alkaline pH:

Platinum as H_2PtCl_6, 10 g/L
Ammonium phosphate, 60 g/L
Ammonium hydroxide to pH 7.5–9
Temperature, 65–75°C
Current density, 0.1–1 A/dm^2
Anodes, platinized

The alkaline formulation can be applied directly to nickel-based alloys without the use of a preplate. Both of the acid baths shown require a preplate, preferably gold, on most basis metals.

RHODIUM PLATING

by Alfred M. Weisberg

Technic Inc., Providence, R.I.

Although several different electrolytic baths for rhodium plating have been proposed the only baths to achieve commercial significance are (1) phosphate for very white and reflective deposits; (2) sulfate for general jewelry and industrial deposits; and (3) mixed phosphate-sulfate for general decorative deposits.

DECORATIVE PLATING

The jewelry and silverware industries were the primary users of rhodium electroplates until quite recently. Although both the phosphate and sulfate baths gave bright white deposits the phosphate bath was preferred for soft-soldered jewelry, especially before the general adoption of bright nickel plating. Cold nickel did not always cover the soft solder, and the acid electrolyte attacked and dissolved some of the solder. Lead in a rhodium bath gave dull, dark deposits and destroyed its decorative white finish. Phosphoric acid attacked the solder less than sulfuric acid did, so phosphate rhodium was preferred. After the introduction of bright nickel most of the industry changed to sulfate because it could operate at a slightly lower rhodium concentration. The phosphate-sulfate solution was used because some considered the color to be a bit whiter or brighter.

The typical rhodium electroplate on costume or precious jewelry is 0.000002 to 0.000005 in. and is produced in 20 sec to 1 min at about 6 V in the following baths.

Phosphate Rhodium Bath

Rhodium as phosphate concentrate, 2 g/L
Phosphoric acid [85% chemically pure (CP) grade], 40–80 ml/L
Anodes, platinum/platinum clad
Temperature, 40–50°C
Agitation, none to moderate
Current density, 2–10 A/dm^2

Sulfate Rhodium Bath

Rhodium as sulfate concentrate, 1.3–2 g/L
Sulfuric acid (95% CP grade), 25–80 ml/L
Anodes, platinum/platinum clad
Temperature, 40–50°C
Agitation, none to moderate
Current density, 2–10 A/dm^2

Phosphate-Sulfate Rhodium Bath

Rhodium as phosphate concentrate, 2 g/L
Sulfuric acid (95% CP grade), 25–80 g/L
Anodes, platinum/platinum clad
Temperature, 40–50°C

Agitation, none to moderate
Current density, 2–10 A/dm^2

Tanks for these baths should all be made of glass, Pyrex, plastic, or plastic-lined steel. If plastic is used it should be leeched once or twice with 5% sulfuric or phosphoric acid for 24 hr before the rhodium is added. In mixing a new solution distilled or deionized water should be used, and the acid should be added to the water carefully and mixed thoroughly before the rhodium concentrate is added. This will prevent precipitation of the rhodium.

Rhodium is, of course, plated out and also lost through drag-out. Because of the expense of rhodium the first rinse after plating should be a stagnant drag-out rinse, also contained in a glass or plastic tank. As water is lost from the plating solution it should be replaced with this drag-out rinse so that some of the "lost" rhodium is returned for reuse. Even with two drag-out tanks the actual amount of rhodium lost will be about 25 to 30% of the rhodium plated; therefore, rhodium should be replenished at the rate of 5 g/18 to 20 ampere-hours (A-hr) of flash plating. Because the drag-out is so high in jewelry plating sulfuric (or phosphoric) acid should also be replenished at the rate of 5 ml/18 to 20 A-hr. This recommended replenishment is only an average value. If possible it should be checked by analysis.

Bright nickel is the preferred base for decorative rhodium electroplates. It provides a bright base for rhodium and also prevents the rhodium solution from attacking a brass, copper, steel, lead, or tin base. All of these metals adversely affect the color and tarnish and corrosion resistance as well as the covering power of the rhodium solution. Nickel, of all the metals, has the least adverse effect on a rhodium solution. Baths can tolerate as much as 1 to 2 g/L and still give a satisfactory deposit. There are no truly satisfactory methods to purify a contaminated rhodium plating solution.

DECORATIVE BARREL PLATING

The usual decorative barrel finish is also 0.000003 to 0.000005 in. A variation of the sulfate-rhodium bath is always used. It is necessary, however, to reduce the metal concentration and to raise the acid concentration to get economical and satisfactory deposits. With many parts in the barrel it is necessary to plate quite slowly so that the parts have time to mix and be evenly exposed to the plating solution. This ensures that they are all plated to a similar thickness before more than 0.000005 in. is deposited. It is not advisable to slow the rate of plating by decreasing the current density (and voltage) because this may lead to nonadhering deposits over a bright nickel base. Therefore, the plating rate is best slowed by decreasing the cathode current efficiency by raising the acid and lowering the rhodium. A typical formulation for decorative barrel plating would be the following:

Rhodium as sulfate concentrate, 1 g/L
Sulfuric acid (95% CP grade), 80 g/L
Anodes, platinum/platinum clad
Temperature, 45–50°C
Current density, 0.5–2 A/cm^2

ELECTRONIC/INDUSTRIAL PLATED RHODIUM

The emerging electrical/electronics industry in the 1950s and 1960s made considerable use of rhodium electrodeposits for many diverse uses, but it was particularly used on sliding and rotating contacts, printed circuit switches and commutators, and high-frequency switches and components.

There are many requirements for rhodium deposits of 0.000020 to 0.0002 in. over nickel or, occasionally, silver. These may be plated from the following solution:

Rhodium metal as sulfate concentrate, 5 g/L

Sulfuric acid (95% CP grade), 25–50 ml/L
Anodes, platinum/platinum clad
Temperature, 45–50°C
Current density, 1–3 A/dm^2
Current efficiency, 70–90% with agitation; 50–60% without agitation

See the previous section under Decorative Plating for instructions on leeching the plating tank before use. It is preferable to use water jacket heating of the solution to prevent local overheating by an immersion heater or steam coil. Even a short exposure to temperatures over 160°F will result in chemical changes to the solution that will result in a permanent increase in stress of the deposit. The stress will be present even if the bath is later operated within the correct temperature range.

Because of the expense of the solution it is advisable to plate with as low a rhodium concentration as possible to achieve the desired plating thickness and finish. If some of the plating is to be 0.0002 in. and over it will be necessary to raise the rhodium concentration to 7½ or 10 g/L.

Replenishment is based on ampere-hours plated and the cathode current efficiency. It is best determined by analytical control; however, an approximation would be to replenish 5 g of rhodium for every 5 to 10 A-hr of plating. The actual value will depend on the average thickness plated an the current density used.

The cathode current efficiency is quite low, even with agitation, and hydrogen gas bubbles will tend to cling to the work and leave imperfections. This effect may be minimized by adding a 1% solution of sodium lauryl sulfate to the bath. The rate of addition should be 1 to 5 ml of a 1% solution per gallon of the plating bath.

INDUSTRIAL BARREL PLATING

Not only the expense of rhodium but the high drag-out of barrel plating recommends the use of a low metal concentration. Coatings in the millionth inch range can be produced with as little as 1 g rhodium/L. Thicker deposits must use proportionally higher concentrations. Deposits of 0.000020 in. may be achieved with 2½ g/L; 0.000050 in. with as little as 3½ g/L; 0.0001 in. with as little as 4 g/L; and deposits of 0.0002 in. and over with 5 g/L. If the holes in the barrel are very small, and the parts have a high surface area, it will be necessary to use higher concentrations to compensate for poor solution transfer.

Otherwise, the formulations for barrel plating are the same:

Rhodium metal as sulfate concentrate, 2.5–5 g/L
Sulfuric acid (CP grade), 20 m/L
Anodes, platinum/platinum clad
Barrels, horizontal, submerged
Temperature, 45–50°C
Current density, 0.5–2 A/cm^2

CARE OF RHODIUM SOLUTION

Contamination of the rhodium solution is the cause of most rhodium plating problems. The major contaminants are (1) organics, (2) rhodium basic salts, (3) rhodium complexes and (4) inorganics such as iron, lead/tin, copper, gold/silver, and nickel.

The most common contaminants are organics such as dust, dirt, adhesives from masking tape, stop-off paints and printed circuit board material, and organics from improperly leached plastic tanks. They are usually easily removed by batch-type carbon treatment. It is imperative that the carbon used be very low in acid-soluble residues. It is also important not to use a diatomaceous earth filter aid. If a single carbon treatment does not clean the solution a second treatment or a treatment with a carbon designed for the removal of very short chain organic molecules may be necessary. Carbon treatment will frequently eliminate stress brittleness and flaking of the deposit. It will also often cure finger staining or apparent tarnishing of the deposit.

Basic rhodium salts will precipitate from a rhodium solution and act as a contaminant if the pH of the bath rises above 2. The acidity of the solution should be controlled and never be allowed to fall below 25 ml/L. If plating is normally done at higher current densities of over 25 A/ft^2 the acidity should be kept even higher. Levels of sulfuric acid of at least 50 ml/L are generally satisfactory. Phosphoric acid is not recommended for industrial plating baths.

Contamination and increased stress by unwanted rhodium complexes, as has been mentioned, can occur if the solution is overheated. Rhodium solutions should be indirectly heated and be thermostatically controlled.

Inorganic contaminants are usually introduced by the basis metal or base plates. The warm sulfuric acid electrolyte is extremely corrosive, and work should never be allowed to hang in the tank without current. Preferably, work should be connected to the negative power source before it is introduced into the rhodium tank. This may occasionally require a flying cathode bar or, in the case of barrel plating, a cathodic battery clamp and wire to be attached to the barrel before it is lowered into the tank. Of course dropped parts should immediately be removed from the bottom of the tank.

Copper, iron, tin, and lead, even after exhibiting a brief brightening effect in the parts per million range, will cause highly stressed heavy rhodium deposits. They will also cause dark and stained deposits and skip plating.

Most metallic impurities, theoretically, can be precipitated from a rhodium solution by potassium ferrocyanide; however, in practice the procedure is very difficult, time-consuming, and not very successful, especially with solutions used for heavy rhodium deposits. The best practice is to prevent metallic contamination.

The parameters that will tend to decrease the stress and brittleness of a rhodium deposit are the following:

1. Increased rhodium metal concentration
2. Increased sulfuric acid concentration
3. Increased temperature
4. Carbon treatment of the bath
5. Decreased inorganic contaminants.

Low-stress rhodium proprietary baths are available that contain trace amounts of selenium and indium. Although the stress and attendant stress cracking are almost totally eliminated, the baths operate like conventional sulfate baths.

RUTHENIUM PLATING

by Alfred M. Weisberg

Technic Inc., Providence, R.I.

Electroplated ruthenium is the second best electrical conductor, produces the hardest deposit, and is the least expensive of the platinum-group metals. In addition it has the highest melting point of the platinum metals that can be deposited from an aqueous solution. Nevertheless, it was not used as an electroplated finish until quite recently. It is used to a limited extent as a barrier layer, a finish on reed switches, and as a novel dark finish on jewelry and other decorative items. A general purpose bath is as follows:

Ruthenium (as sulfamate or nitrosyl sulfamate), 5.3 g/L
Sulfamic acid, 8 g/L
Anodes, platinum
pH, 1–2
Temperature, 80–140°F (sulfamate); 70–190°F (nitrosyl sulfamate)
Current density, 10–30 A/ft^2
Current efficiency, 20%
Time to plate 0.0001 in. 30–40 min at 20 A/ft^2

The lost pH of this solution requires that the ruthenium be plated over a gold or palladium flash. Decorative flash deposits may be produced from the following:

Ruthenium (as nitroso salt), 2.0 g/L
Sulfuric acid, 20 g/L
Current density, 20–30 A/ft^2
Temperature, 120–180°F

This bath also requires a flash underplate of gold.

The hardness of ruthenium deposits can be 800 to 1,300 Knoop hardness number, harder than a rhodium deposit; however, ruthenium has less internal stress.

SILVER PLATING

by Alan Blair

Lucent Technologies, Staten Island, N.Y.

The majority of silver-plating solutions in use today are remarkably similar to those patented by the Elkington brothers in 1840. Even in these environmentally aware days, cyanide-based silver-plating solutions offer the most consistent deposit quality at the lowest cost.

Silver anodes dissolve readily in electrolytes containing free cyanide and the consumption of brighteners or grain refiners is generally low, making these processes very economical to operate in spite of waste treatment costs. High-speed silver-plating solutions that employ insoluble anodes are well established, and, even though these contain no free cyanide, potassium silver cyanide remains the source of the metal. Truly cyanide-free silver-plating solutions have been sought after for many years. Several formulations are workable and are described below.

CYANIDE SYSTEMS

A typical, traditional silver-plating solution suitable for rack work would be as follows:

Silver as KAg(CN), 15–40 g/L (2.0–5.5 oz/gal)
Potassium cyanide (free), 12–120 g/L (1.6–16 oz/gal)
Potassium carbonate (min), 15 g/L (2 oz/gal)
Temperature, 20–30°C (70–85°F)
Current density, 0.5–4.0 A/dm^2 (5–40 A/ft^2)

Barrel plating usually results in much greater drag-out losses and lower current density during operation so lower metal concentrations are desirable. A typical formula would be:

Silver as KAg(CN), 5–20 g/L (0.7–2.5 oz/gal)
Potassium cyanide (free), 25–75 g/L (3.3–10.0 oz/gal)
Potassium carbonate (min), 15 g/L (2 oz/gal)
Temperature, 15–25°C (60–80°F)
Current density, 0.1–0.7 A/dm^2 (1–7.5 A/ft^2)

The formulas above will produce dull, chalk-white deposits that are very soft (less than 100 Knoop). Additions of grain refiners or brighteners will modify deposits causing them to become lustrous to fully bright.

Examples of these additives are certain organic compounds, which usually contain sulfur in their molecule, and complexed forms of a group VA or VIA element such as selenium, bismuth, or antimony. Deposits become harder as brightness increases; the usual hardness range will be between 100 and 200 Knoop. Antimony and selenium will produce harder deposits than most organic compounds, although the latter generally have better electrical properties.

Carbonate is an oxidation product of cyanide, so additions are not needed after the initial solution makeup. This oxidation occurs slowly even when the solution is not in use, and when the potassium carbonate concentration has reached 120 g/L (16 oz/gal) deposits can become dull or rough. Removal of carbonate can be accomplished by freezing-out or precipitation with calcium or barium salts.

Silver is a relatively noble metal, and as such will form immersion deposits on the surfaces of less noble metals that are immersed in its solution. This tends to happen even when

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the base metal enters the silver solution "hot" or "live," that is, with a voltage already applied. The inevitable result of this phenomenon is poor adhesion of subsequent deposits. To minimize this effect, it is essential to employ a silver strike coating prior to the main deposit. A typical silver strike would be as follows:

Silver as $KAg(CN)_2$, 3.5–5 g/L (0.5–0.7 oz/gal)
Potassium cyanide (free), 80–100 g/L (10–13 oz/gal)
Potassium carbonate (min), 15 g/L (2 oz/gal)
Temperature, 15–25°C (60–80°F)
Current density, 0.5–1.0 A/dm^2 (5–10 A/ft^2)

It is not necessary to rinse between such a strike and a cyanide-based silver-plating solution. Silver strike thickness is typically 0.05–0.25 μm (0.000002–0.000010 in.).

Anode purity is of paramount importance since typical impurities, such as copper, iron, bismuth, lead, antimony, sulfur, selenium, tellurium, and platinum-group metals will cause solution contamination and may lead to anode filming, which inhibits proper dissolution of the silver. Silver anodes are produced by rolling, casting, or extruding the metal. Care should be taken to ensure adequate annealing has taken place after fabrication. The object of annealing is to obtain correct grain size so that the anodes do not shed during dissolution. (Shedding means that small particles break away from the anode, and these can cause roughness in the silver deposit.)

Insufficient concentration of free cyanide and insufficient anode area will cause anodes to shed or dissolve improperly. Cyanide concentration should be analyzed regularly and additions of potassium cyanide made as needed. Optimum anode to cathode area ratio is 2:1; a maximum anode current density of 1.25 A/dm^2 (13.5 A/ft^2) is recommended.

HIGH-SPEED SELECTIVE PLATING

Electronic components such as lead frames are usually plated with silver using selective methods. Silicon chips and aluminum wires can be bonded to the silver by employing ultrasonic or thermosonic bonding techniques. Silver thickness ranges 1.875 to 5.0 μm (0.000075–0.000200 in.), with deposition times between 1 and 4 sec.

The small areas to be plated demand the use of insoluble anodes. Platinized-titanium mesh and platinum wire are examples of anode materials in common use. Traditional cyanide silver electrolytes suffer rapid degradation under these conditions, oxidation and polymerization of the cyanide at the inert anodes being the principal cause. Special solutions were developed to overcome this situation; these contain essentially no free cyanide but still depend on potassium silver cyanide as the source of silver. A typical formula is as follows:

Silver as $KAg(CN)_2$, 40–75 g/L (5–10 oz/gal)
Conducting/buffering salts, 60–120 g/L (8–16 oz/gal)
pH, 8.0–9.5
Temperature, 60–70°C (140–160°F)
Current density, 30–380 A/dm^2 (300–3,500 A/ft^2)
Agitation, Jet plating
Anodes, Pt or Pt/Ti

Conducting salts can be orthophosphates, which are self-buffering, or nitrates, which require additional buffering from borates or similar compounds. Buffering is important in these solutions since there is a significant drop in pH at the inert anode during plating due to destruction of hydroxide ions. Insoluble silver cyanide forms on the anode surface as a result of cyanide depletion in this locally low pH. Plating current drops off rapidly due to polarization. The following equations summarize the reactions involved.

$$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$$

$$Ag(CN)^-_2 \rightarrow AgCN\downarrow + CN^-$$

Other additives include grain refiners, for example, selenium, and anti-immersion agents. The latter inhibit chemical deposition onto unplated areas of the lead frames. They are usually based on a mercaptan or similar compound, which will attach itself to the active base metal surface.

NONCYANIDE SYSTEMS

Many compounds of silver have been investigated as potential metal sources for a noncyanide plating process. Several authors have subdivided these studies into three groups by compound type. These groups are (1) simple salts, e.g., nitrate, fluoborate, fluosilicate; (2) inorganic complexes, e.g., iodide, thiocyanate, thiosulfate, pyrophosphate, trimetaphosphate; and (3) organic complexes, e.g., succinimide, lactate, thiourea. The simple salts all appear to suffer from the same problem: light sensitivity of the materials. Although some smooth deposits have been obtained from such systems, they are not viable under normal production conditions.

Of the inorganic complexes considered, three are worth discussing further. These are the iodide, trimetaphosphate, and thiosulfate solutions.

Iodide Solutions

Several authors report some success with baths that are quite similar. A typical solution might be as follows:

Silver iodide, 20–45 g/L (2.5–6.0 oz/gal)
Potassium iodide, 300–600 g/L (40–80 oz/gal)
HI or HCl, 5–15 g/L (0.7–2 oz/gal)
Gelatin (optional), 1–4 g/L (0.15–0.55 oz/gal)
Temperature, 25–60°C (80–140°F)
Current density, 0.1–15 A/dm^2 (1.0–150 A/ft^2)

Without exception these authors found iodine in deposits from their particular formula. This fact, and the relatively high price of the iodide salts, has prevented further use of this type of solution.

Trimetaphosphate Solution

A process was developed for silver plating magnesium and its alloys; its use on other metals is not reported.

Silver trimetaphosphate (monobasic), $Ag_2HP_3O_9$, 3–45 g/L (0.40–0.60 oz/gal)
Sodium trimetaphosphate (trimer), $Na_6P_6O_{18}$, 100–160 g/L (13.5–21.5 oz/gal)
Tetrasodium pyrophosphate, $Na_4P_2O_7$, 50–175 g/L (6.7–23.5 oz/gal)
Tetrasodium EDTA, 35–45 g/L (4.7–6.0 oz/gal)
Sodium fluoride, 3–5 g/L (0.40–0.70 oz/gal)
pH (adjust with triethanolamine or sodium bicarbonate), 7.9–9.5
Temperature, 50–60°C (120–140°F)
Current density, 0.5–2.5 A/dm^2 (5–25 A/ft^2)

Thiosulfate Solutions

Thiosulfate-based formulas have proven to be the most successful of any inorganic complex investigated. Early attempts to plate silver from such a solution resulted in rapid oxidation of the complex and precipitation of insoluble silver compounds. Additions of sodium metabisulfite were found to minimize this tendency, and all thiosulfate-based processes now contain this ingredient.

Solution composition can be expressed:

Silver as thiosulfate, 30 g/L (4.0 oz/gal)
Sodium thiosulfate, 300–500 g/L (40–70 oz/gal)
Sodium metabisulfite, 30–50 g/L (4.0–6.7 oz/gal)
pH (adjust with sodium bisulfite or hydroxide), 8–10
Temperature, 15–30°C (60–85°F)
Current density, 0.4–1.0 A/dm^2 (4–10 A/ft^2)

These electrolytes can be operated with stainless steel or silver anodes; however, the latter should be bagged.

Problems of poor adhesion can be overcome by using a conventional silver strike or one in which there is no free cyanide. In either case, rinsing before entry into the thiosulfate solution is a good practice. A small amount of cyanide drag-in will react with thiosulfate in the solution to form thiocyanate:

$$\mathrm{CN-} + \mathrm{S2O3-2} \rightarrow \mathrm{CNS-} + \mathrm{SO3-2}$$

One reported advantage of thiosulfate over cyanide systems is that thickness distribution is better on complex-shaped objects. However, deposits seem to tarnish in air much quicker than cyanide-produced ones. Postplating passivation is recommended.

Succinimide Solutions

Several electrolytes based on this organic complex of silver have been patented, two of which are described below:

Silver as potassium silver disuccinimide, 30 g/L (4.0 oz/gal)
Succinimide, 11.5–55 g/L (1.5–7.4 oz/gal)
Potassium sulfate, 45 g/L (6.0 oz/gal)
pH, 8.5
Temperature, 25°C (77°F)
Current density, 1 A/dm^2 (10 A/ft^2)

Potassium nitrite or nitrate can be substituted for the sulfate and the addition of amines, such as ethylene diamine or diethylenetriamine, and wetting agents produce bright, stress-free deposits.

Silver as potassium silver disuccinimide, 24 g/L (3.3 oz/gal)
Succinimide, 25 g/L (3.4 oz/gal)
Potassium citrate, 50 g/L (6.7 oz/gal)
pH, 7.5–9.0
Temperature, 20–70°C (70–160°F)
Current density, 0.54 A/dm^2 (5.5 A/ft^2)

Potassium borate may be used in place of potassium citrate.

Tarnish resistance of deposits obtained from these processes is inferior to that of deposits produced from cyanide electrolytes.

Organic Solvent Solutions

Nonaqueous solvents enable investigation of silver plating from salts that are insoluble in water. One such system, based on dimethylformamide (DMF), is illustrated below:

Silver chloride, 10 g/L (1.3 oz/gal)
Thiourea, 30 g/L (4.0 oz/gal)
Aluminum chloride, 10 g/L (1.3 oz/gal)
Solvent dimethylformamide, balance

Room temperature
Current density, <1.5 A/dm^2 (<15 A/ft^2)

Milky white silver deposits were obtained from a small volume of this solution over an extended time period; however, some scale-up problems are inevitable with such a system.

SUMMARY

After more than 150 years, silver plating is still performed using a cyanide electrolyte that resembles the electrode in the original 1840 patent. Most of the work directed at replacing cyanide in silver plating has resulted in little more than technical interest. As yet, no production-proven, noncyanide alternative has been found, although systems based on thiosulfate and succinimide appear to offer some promise. Both of these systems are commercially available.

TIN, LEAD, AND TIN-LEAD PLATING

by Stanley Hirsch

Leeam Consultants Ltd., New Rochelle, N.Y.

and Charles Rosenstein

AMZA Ltd., Holon, Israel

Tin and tin-lead alloys are solderable and, therefore, are used extensively in the electronics industry to bond electronic components. This precludes the need for strong fluxes to wet the deposit. Tin and lead can be codeposited easily because of the closeness of their standard electrode potentials. Tin and tin-lead deposits must possess all of the following characteristics: good solderability and reflowability; low porosity; good corrosion resistance; and uniformity of alloy composition, thickness, smoothness, and appearance, over a wide current density range.

ADDITIVES

Organic additives are required in *all* tin, lead, and tin-lead electroplating solutions to produce a useful deposit. In the absence of additives, treed, nonadherent, and nodular deposits result; therefore, additives are *absolutely essential* in order to yield smooth, uniform deposits and to impart good throwing power.

Additives are depleted during plating and must be routinely replenished. Electrolysis causes some decomposition of the organics, resulting in their occlusion in the deposit. If present in sufficiently large amounts in the deposit, organics can cause solderability and reflow problems. Accelerated aging tests are performed on tin and tin-lead deposits to help predict their shelf life, as components are sometimes used long after they are plated.

TIN, LEAD, AND TIN-LEAD PLATING BATHS

Tin, lead, and tin-lead electroplating solutions are used to plate components in numerous engineering, communications, military, and consumer product applications.

Tin Barrel, Still, and High-Speed Baths

These baths are well suited for electrolytic tin plate and are used to plate transistors, semiconductors, various electronic parts, refrigerator parts, and kitchenware. Higher temperatures permit higher current densities and wire speeds.

Lead Barrel and Still Baths

Lead baths are used in the plating of bearings, connectors, internal and conforming anodes for chromium plating, valves, seals, and parts for storage batteries. Because lead deposits are soft, slow barrel speeds are recommended in order to prevent heavy parts from bonding to one another.

Table I. Concentrations of Fluoboric Acid, Lead Fluoborate, Stannous Fluoborate, and Copper Fluoborate Used in Tin, Lead, and Tin-Lead Alloy Plating

Product	*Concentration (g/L)*	*Specific Gravity (20°C)*
48% Fluoboric Acid		1.365
Fluoboric Acid, 100%	656	
Boric Acid	19	
51% Lead Fluoborate		1.710
Lead	480	
Fluoboric Acid, 100%	11	
Boric Acid	48	
50% Stannous Fluoborate		1.600
Stannous Tin	320	
Fluoboric Acid, 100%	48	
Boric Acid	48	
45% Copper Fluoborate		1.550
Copper	187	
Fluoboric Acid, 100%	30	
Boric Acid	30	

60 Tin/40 Lead Solder Barrel, Still, and High-Speed Baths

The high throw of the baths and the excellent solderability and shelf life of the deposit make these baths suitable for use on printed circuit boards, connectors, and other specialized electrical devices. The high-speed bath is used for reel-to-reel applications, such as wire and strip plating.

90 Tin/10 Lead Barrel, Still, and High-Speed Baths

This bath provides a uniform, smooth matte deposit, which is used for various engineering applications. Higher temperatures permit higher current densities, which are required in wire and strip plating.

93 Lead/7 Tin Barrel and Still Baths

Deposits plated from 93 lead/7 tin baths are harder than those obtained from lead baths. The 93 lead/7 tin bath is used to plate bearings and seals. Since 93 lead/7 tin alloys are soft, slow barrel speeds are recommended in order to prevent heavy parts from bonding to one another.

10 Tin/88 Lead/2 Copper Ternary Alloy Barrel and Still Baths

The operation of the ternary alloy bath is similar to that of the 93 lead/7 tin bath. The ternary alloy deposit results in bearing metals that exhibit a greater resistance to fatigue than do the 93 lead/7 tin alloys. The alloy is used to plate linings in sleeve bearings.

FLUOBORATE PLATING

Tin fluoborate, lead fluoborate, and fluoboric acid, in various proportions (see Tables I and II), can be used for plating all percentages of tin-lead, 100% lead, and 100% tin. Fluoborate baths require boric acid for stability. Anode bags filled with boric acid are hung in the plating tanks. Stabilized liquid peptone, gelatin, resorcinol, or other liquid organic additives *must be* added to tin, lead, and tin-lead baths to produce smooth, nontreeing deposits

Table II. Fluoborate Bath Compositions and Operating Parameters[a]

	HBF_4 (g/L)	Tin (g/L)	Lead (g/L)	Copper (g/L)	Additive	Temperature °F (°C)	Current Density (A/ft^2)	Anode to Cathode Ratio	Anodes
Tin Bath:									
Barrel and still:									
Range	188–263	30–45	—	—	As required	90–120	1–80	1:1	Pure tin
Optimum	225	37				(32–49)			
Wire and strip:									
Range	225–300	45–60	—	—	As required	90–130	1–300	1:1	Pure tin
Optimum	263	53				(32–54)			
Lead Barrel and Still Baths:									
Range	15–30	—	195–239	—	As required	70–100	20–70	1:1	Pure lead
Optimum	23		218			(21–38)			
60 Tin/40 Lead Solder Bath:									
Barrel and still:									
Range	98–150	53–60	23–30	—	As required	70–85	25–35	2:1	60 tin/40 lead
Optimum	124	56	26			(21–29)			
High Throw:									
Range	350–500	12–20	8–14	—	As required	70–100	15–25	2:1	60 tin/40 lead
Optimum	425	16	11			(21–38)			
90 Tin/10 Lead Barrel and Still Baths:									
Range	150–200	70–80	8–12	—	As required	70–100	1–80	1:1	90 tin/10 lead
Optimum	175	75	10			(21–38)			
93 Lead/7 Tin Barrel and Still Baths:									
Range	15–30	10–20	195–239	—	As required	70–100	20–70	1:1	93 lead/7 tin
Optimum	23	15	217			(21–38)			
10 Tin/88 Lead/2 Copper Barrel and Still Baths:									
Range	20–40	8–12	135–150	1.5–2.5	As required	70–100	20–70	1:1	10 tin/88/lead/2 copper, or
Optimum	30	10	143	2		(21–38)			90 lead/10 tin, or pure lead

[a] Agitation required, mechanical or barrel; vigorous for high-speed plating.
Periodic filtration through 1-μm Dynel or polypropylene cartridges.
Tanks, pumps, and filters made from polyethylene, polyvinyl chloride (PVC), or Koroseal.
Heating and cooling equipment made from Karbate or Teflon.

Table III. Concentrations of Methane Sulfonic Acid (MSA) and MSA Salts Used in Tin, Lead, and Tin-Lead Alloy Plating

Product	*Concentration (g/L)*	*Specific Gravity (20°C)*
50% MSA	MSA 100% = 613	1.225
70% MSA	MSA 100% = 945	1.350
Stannous methane sulfonate	Sn = 120	1.230
	Sn = 150	1.285
	Sn = 200	1.390
	Sn = 240	1.450
	Sn = 300	1.560
Lead methane sulfonate	Pb = 450	1.630
	Pb = 500	1.700
Copper methane sulfonate	Cu = 100	1.260

and to increase the throwing power of the plating bath. These additives are mandatory, as fluoborate baths cannot function without them.

METHANE-SULFONIC-ACID-BASED PLATING

Methane sulfonic acid (MSA)-based electroplating systems gained commercial acceptability during the early 1980s. Various plating baths and additives have been developed. Each MSA bath requires a custom-made additive for that specific content of tin, lead, and MSA in order to obtain a useful deposit. As with fluoborates, metal salts of MSA are very soluble and various concentrations of MSA and its metal salts are available (see Tables III and IV).

Troubleshooting guidelines for fluoborate- and MSA-based tin, lead, and tin-lead plating baths are given in Tables V to VII. The troubleshooting table for acid-tin-based baths (Table V) is also applicable to stannous sulfate baths.

TIN PLATING FROM STANNOUS SULFATE BATHS

The stannous sulfate bath contains stannous sulfate, sulfuric acid, and additives (see Table VIII). Advantages of this bath are its good throwing power, high cathode efficiency, operation at room temperature, and ease of control.

Addition agents are essential for the operation of this bath. They inhibit the oxidation of stannous tin, produce smooth, dense deposits, and prevent treeing. Among those in use are phenol- or cresol-sulfonic acid, gelatin, β-naphthol, and resorcinol. Several proprietary additives are also available.

Bright tin deposits are obtained through the addition of proprietary additives. Solderability, corrosion resistance, and leveling characteristics are essentially the same in bright or matte plating. It is questionable whether bright tin plating is superior to matte in resistance to whisker growth and tin pest, as has been claimed. Refer to Table V for troubleshooting.

TIN PLATING FROM STANNATE BATHS

Alkaline baths are also used for tin plating, with sodium stannate and potassium stannate as the two available baths (see Table IX). Both will produce similar satisfactory results. The criteria for choosing one over the other are related to cost and speed of plating.

Table IV. Methane Sulfonic Acid (MSA) Bath Compositions and Operating Parameters[a]

	MSA (g/L)	*Tin (g/L)*	*Lead (g/L)*	*Copper (g/L)*	*Additive*	*Temperature °F (°C)*	*Current Density (A/ft^2)*	*Anodes*
Tin Barrel, Still, and High-Speed Baths:								
Range	200–250	35–55	—	—	As required	70–130	1–250	Pure tin
Optimum	225	45				(21–54)		
Lead Barrel and Still Baths:								
Range	30–50	—	56–72	—	As required	70–100	1–40	Pure lead
Optimum	40		64			(21–38)		
60 Tin/40 Lead Solder Bath:								
Barrel and still:								
Range	200–250	12–20	6–10	—	As required	70–85	1–40	60 tin/40 lead
Optimum	225	16	8			(21–29)		
High speed:								
Range	200–250	12–20	8–12	—	As required	70–100	1–250	60 tin/40 lead
Optimum	225	16	10			(21–38)		
90 Tin/10 Lead Barrel, Still, and High-Speed Baths:								
Range	200–250	17–25	2–4	—	As required	70–130	1–250	90 tin/10 lead
Optimum	225	21	3			(21–54)		
93 Lead/7 Tin Barrel and Still Baths:								
Range	30–50	4–5	56–72	—	As required	70–85	1–40	93 lead/7 tin
Optimum	40	4.5	64			(21–29)		
10 Tin/88 Lead/2 Copper Barrel and Still Baths:								
Range	30–50	4–5	65–75	0.8–1.2	As required	70–100	1–40	10 tin/88 lead/2 copper, or 90 lead/10 tin, or pure lead
Optimum	40	4.5	70	1.0		(21–38)		

[a] Agitation required, mechanical or barrel; vigorous for high-speed plating.
Platinized titanium anodes can be substituted for the soluble anodes.
Periodic filtration through 1-μm Dynel or polypropylene cartridges.
Anode to cathode ratios for all baths is 1:1.
Tanks, pumps, and filters made from polyethylene, polyvinyl chloride (PVC), or Koroseal.
Heating and cooling equipment made from Karbate or Teflon.

Table V. Troubleshooting Acid-Tin-Based Baths

Problem	*Cause*	*Remedy*
Treeing	Low additive	Add additive.
	Low acid	Increase acid.
Roughness	Organic contamination	Carbon treat.
	Solids in bath	Filter.
	Metallic contamination	Dummy bath.
	Stannic tin	Filter and exclude air from bath.
Graininess	Low additive	Add additive.
	Low tin	Increase tin.
Burning	Low acid	Increase acid.
	Too high current density	Lower current density.
	Low additive	Add additive.
Streaking or pitting	Low additive	Add additive.
Poor throw	Low additive	Add additive.
	Low acid	Increase acid.
	Low tin	Increase tin.
Gassing	Too high current density	Lower current density.
	Low additive	Add additive.
	Organic contamination	Carbon treat.
	Low tin	Increase tin.
	Low temperature	Increase temperature.
Lack of adhesion	Poor cleaning	Correct cleaning cycle.
Brittle deposits	Organic contamination	Carbon treat.
Dark deposit	Low temperature	Increase temperature.
	Low additive	Add additive.
	Organic contamination	Carbon treat.

Table VI. Troubleshooting Lead-Based Baths

Problem	*Cause*	*Remedy*
Treeing	Low lead	Increase lead.
	Low additive	Add additive.
Poor throw	Low lead	Increase lead.
	Low additive	Add additive.
Roughness	Metallic contamination	Dummy the bath.
	Solids in bath	Filter bath.
	Too high current density	Lower current density.
	Low agitation	Increase agitation.
	Low additive	Add additive.
	Low acid	Increase acid.
	Chloride/sulfate contamination	Filter bath and check cleaning cycle.
Lack of adhesion	Poor cleaning	Correct cleaning cycle.
Dark deposit	Organic contamination	Carbon treat.
Thin deposit	Low lead	Increase lead.
	Too low current density	Increase current density.
Mossy deposit (ternary alloy only)	Excess copper in bath	Analyze and adjust copper.

Table VII. Troubleshooting 60 Tin/40 Lead Solder Baths

Problem	*Cause*	*Remedy*
Poor throw	Low tin and lead	Increase tin and lead.
	Low acid	Increase acid.
	Low additive	Add additive.
	High anode to cathode ratio	Remove several anodes.
	Organic contamination	Carbon treat.
Gassing	Too high current density	Lower current density.
	Organic contamination	Carbon treat.
Treeing	Low additive	Add additive.
	Low acid	Increase acid.
Lack of adhesion	Poor cleaning	Correct cleaning cycle.
Burning	Low tin and lead	Increase tin and lead.
	Low acid	Increase acid.
	Too high current density	Lower current density.
Graininess	Organic contamination	Carbon treat.
Roughness	Organic contamination	Carbon treat.
	Solids in bath	Filter.
	Stannic tin	Filter and exclude air from bath.
	Chloride/sulfate contamination	Filter bath and check cleaning cycle.
Incorrect alloy	Metallic contamination	Dummy the bath.
	Low acid	Increase acid.
	Wrong current density	Use correct current density.
	Improper agitation	Use proper agitation.
	Incorrect anodes	Use anodes with correct composition.
	Incorrect tin to lead ratio	Analyze bath and correct ratio.
Unsatisfactory reflow	Incorrect thickness	Use correct plating time.
	Dewetting caused by:	
	Poor cleaning	Correct cleaning cycle.
	Organic contamination	Carbon treat.
	High reflow temperature	Use proper temperature.
	Incorrect alloy	See Problem: "Incorrect alloy" above.

Table VIII. Stannous Sulfate Bath Composition and Operating Conditions

	Range (g/L)	*Optimum (g/L)*
Tin	30–50	40
Sulfuric acid, 100%	100–140	120
Additive	As recommended by manufacturer	
Anodes	Pure tin	
Current density, A/ft^2	1–25	
Anode to cathode ratio		1:1
Temperature, °F (°C)	70–85 (21–29)	
Agitation	Cathode and solution	
Filtration	1 μm Dynel or polypropylene cartridges	
Pumps and tanks	Polyethylene, polypropylene, rubber	
Heaters and coolers	Karbate	

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Table IX. Stannate Baths Composition and Operating Conditions

	Rack (g/L)	*Barrel (g/L)*
Sodium Stannate Bath:		
Sodium stannate	90	180
Tin	40	80
Free sodium hydroxide	12	23
Cathode current density, A/ft^2	15–20	5–15
Anode current density, A/ft^2	25	15–25
Voltage	3–4	3–4
Temperature, °F (°C)	170–180 (77–82)	165–175 (74–79)
Potassium Stannate Bath:		
Potassium stannate	100	200
Tin	40	80
Free potassium hydroxide	15	23
Cathode current density, A/ft^2	30–100	1–100
Anode current density, A/ft^2	30–40	10–30
Voltage	4–8	4–14
Temperature, °F (°C)	150–180 (66–82)	150–180 (66–82)
Sodium and Potassium Stannate Baths:		
Anode to cathode ratio	1:1	
Filtration	25 μm Dynel or polypropylene cartridges	
Agitation	Cathode and solution	
Pumps and tanks	Stainless steel, low-carbon steel, polypropylene, polyethylene	
Heaters and coolers	Low-carbon steel, polypropylene, polyethylene	

Potassium stannate is generally preferred over sodium stannate for the following reasons:

1. Higher plating rates.
2. Greater conductivity, especially in barrel plating.
3. Less potential for sludge formation.

The plater is cautioned to choose one or the other bath, and not to mix them. Potassium hydroxide should be used with the potassium stannate bath and sodium hydroxide with the sodium stannate bath. Although the "mixed" bath is operable and satisfactory results can be obtained, analytical control is quite difficult.

Anodes in Stannate Baths

Anodes used in stannate baths are made of pure tin, tin alloyed with 1% aluminum (known as "high-speed" anodes), or inert materials such as steel, nickel, or stainless steel. Advantages of the high-speed anode are its greater current density range and its consistent efficiency at higher current density.

The formation and maintenance of the anodic film is critical to the operation of the stannate bath. The primary cause of poor tin deposits is the improper filming of the anodes.

Table X. Stannate Anode Film Characteristics

	Pure Tin	*Tin + 1% Al (High Speed)*	*Inert Anode*
Color of film formed	Yellowish	Olive green	No film
Anode current density, A/ft^2	15–40	30–80	No limits

To film tin anodes, a "surge" of current, at higher than normal current density, must be impressed on them for a few seconds to a minute, after which the current is reduced to its regular value (see Table X). The anodes must be refilmed after each shut-down period prior to plating, as the film dissolves rather quickly. Practically all problems in the operation of a stannate bath are resolved when proper anode operation is achieved.

Inert anodes are advantageous in that they avoid the difficulty of filming and they inhibit the formation of harmful stannous tin by producing oxygen at the anode. Furthermore, they do not change shape in use. Their use has previously been somewhat limited because of the need for chemical replenishment of the bath as more tin is consumed. Replenishment of the tin content of the bath by a tin oxide solution has made the use of inert anodes practical in potassium stannate systems only.

Operation of Stannate Baths

Stannate solutions should be light straw or light gray in color. Black solutions indicate the presence of stannous tin, and they should be treated with hydrogen peroxide (2 ml 35% hydrogen peroxide per gallon of solution). If frequent additions of peroxide are necessary, make sure the hydroxide concentration is not too high and/or the anode current density is not too low.

A 10% solution of acetic acid is used to lower the free hydroxide content of the bath; one gallon of 10% acetic acid will neutralize 9.25 ounces of sodium hydroxide or 12.75 ounces of potassium hydroxide. Acetic acid must be added slowly, with constant stirring, so that the stannic acid formed will redissolve.

Filtration of stannate baths is very difficult. Sludge removal should be done when parts being plated are rough from occluded dirt. Sludge usually consists of hydrated tin oxide and carbonates. Allow the bath to cool and settle overnight, decant the clear solution to another tank, and shovel out the remaining sludge. Refer to Table XI for troubleshooting.

REFLOWING TIN DEPOSITS

Tin can be plated either matte or bright. Although the characteristics of each are comparable, bright tin plating has its proponents and is quite successful, commercially.

Converting the matte finish of tin plate to a bright one can be accomplished by means of a process called reflowing, flow melting, or flow brightening. The tin coating is heated momentarily to a temperature slightly above its melting point of 450°F, and then quickly quenched to produce the bright finish.

Among the methods used in heating the plated material are induction, conduction, radiant heating, and immersion. The most commonly used is immersion in hot oil or fat for a short time. Typical operating conditions are given in Table XII. The oil is usually a long chain fatty acid ester of glycerin such as tallow, palm oil, or partially hydrogenated oil, which has a sufficiently high flash point for the temperature used. It should also have some free fatty acid to serve as a flux.

It is best to reflow as soon as possible after plating. The heating to the molten stage should be completed within 2 to 10 seconds before removing and quenching. For best results, the time to melt the tin coating should be precisely calculated. Unsatisfactory results, in the form of dewetting or balling-up, can occur if the parts are left in the oil too long after the coating melts. The size of the oil bath is also important so that the immersion of cold parts does not reduce the oil temperature to the point that heating time must be prolonged.

A suitable quench to use is 4 to 6 in. of kerosene (acid-free) over water. The parts should be lowered into the quench slowly so that the molten tin coating solidifies in the kerosene layer. A spangled appearance will result if the molten tin comes in contact with the water. The water further lowers the temperature of the parts and also keeps the kerosene from being heated too near its flash point. The kerosene also serves to remove some of the oil from the tin surface.

Table XI. Troubleshooting Stannate Baths

Problem	*Cause*	*Remedy*
Anodes gray or white	Initial current density too low to form film.	Remove anodes and replace one at a time when current is on.
Anodes brown or black, film passive	Low free hydroxide	Add KOH or NaOH.
	Low temperature	Increase temperature.
	High anode current density	Add anodes. If above does not remove film, dip anodes in a 20% hydrochloric acid solution and rinse well before using.
Excessive anodic gassing	Low temperature	Increase temperature.
	High anode current density	Add anodes.
Film lost after first forming	High free hydroxide	Add 10% acetic acid.
	Low anode current density	Remove some anodes.
	High temperature	Lower temperature.
	Poor anode contact	Clean contact.
No anodic film	Initial current density too low to form film	Remove anodes and replace one at a time when current is on.
Low cathode efficiency	Low temperature	Increase temperature.
	Low tin	Add stannate.
	High free hydroxide	Add 10% acetic acid.
	High current density	Lower current density.
Low anode efficiency	Low temperature	Increase temperature.
	Low free hydroxide	Add KOH or NaOH.
	High current density	Lower current density or add more anodes.
Narrow plating range	Low temperature	Increase temperature.
	Low tin	Add stannate
	Potassium bath	Add stannate.
	Sodium bath	Switch to potassium bath.
Low conductivity	Low temperature	Increase temperature.
	Low free hydroxide	Add KOH or NaOH.
	Low tin	Add stannate.
Nonadherent deposits	Initial current density too low to form film	Remove anodes and replace one at a time when current is on.
Solution crystallizes	High carbonates	Freeze out carbonates and then filter.
Rough, dark, or spongy deposits	Stannous tin in solution	Treat with hydrogen peroxide.

Small parts generally are immersed in the hot oil in bulk in a suitable basket. They are then separated by pouring them slowly into the quench or by using a breaker, which separates them before entering the quench. For flow-melting large parts, a compartment basket is recommended to prevent disfiguration of parts touching while the tin is molten.

The breakdown of free fatty acid content will gradually reduce the effectiveness of the oil, relative to whether it drains freely and evenly from the molten surface or whether a

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Table XII. Operating Conditions for Tin Reflowing

	Optimum	*Range*
Plating thickness, in.	0.00025	0.0001–0.0003
Immersion time, sec.	6	2–10
Temperature of oil bath, °F	490	480–510
Acid neutralization value, mg KOH/g of oil	2.7	2.3–6.6

Table XIII. Troubleshooting for Tin Reflowing

Problem	*Cause*	*Remedy*
Etching	Acid neutralization value too high	Remove part of oil bath and replace with new oil.
Dewetting	Tin coating too thick Part not cleaned well before plating	Plate for shorter time. Check cleaning cycle.
Streaky	Acid neutralization value too low	Add fatty acid flux.
Not fully bright	Tin coating too thin	Plate for longer period of time.
Spangling	Molten tin comes in contact with water in quench	Increase in quench. Lower parts more slowly.

streaked appearance occurs. To maintain the oil suitably for proper draining, part of it (10–25%) must be replaced frequently.

Residual oil must be removed from the tin surface after flow melting. Any ordinary degreasing method may be used, but the preferred method is vapor degreasing.

There are a number of factors that are critical in successful reflowing. Good cleaning, good plating, and good rinsing practices are vital. Dewetting is more likely to occur on large flat areas, rather than with rounded shapes. Troubleshooting hints are offered in Table XIII.

Determination of Acid Neutralization Value

1. Weigh 6 to 10 grams of oil in a 250-ml Erlenmeyer flask and add approximately 50 ml of 3A alcohol (a methanol-ethanol mixture) previously neutralized to a pH of 7.0.
2. Carefully heat the solution on a hot plate while stirring until one or two bubbles appear on the surface of the solution.
3. Remove the solution from the hot plate, add five drops phenolphthalein indicator, and immediately titrate with 0.1 N sodium hydroxide from clear to a pink endpoint that persists for 10 seconds.

Acid Neutralization Value mg KOH/g oil = ml Na/OH × 5.611/weight oil sample, g

TIN-NICKEL ALLOY PLATING

by S. K. Jalota

Olin Corp., New Haven, Conn.

An alloy of tin and nickel can be electroplated directly on copper, copper alloys, nickel, and undercoats of copper and nickel on ferrous and zinc diecast substrates. The tin-nickel alloy is a single-phase metastable compound of ~65% tin and ~35% nickel by weight, which corresponds to an equiatomic ratio of one part tin and one part nickel. The tin-nickel alloy is nonmagnetic and nonallergic to skin. It finds application in replacing chromium in decorative and light engineering industries and in printed circuit boards as an etch resist. The nonallergic property allows it to replace electroplated nickel on fasteners for garments. Electroplating is accomplished mainly from aqueous solutions containing stannous (tin) chloride, nickel chloride, and ammonium bifluoride maintained at 2 to 5 pH and ~55 to 70°C (~130–160°F) with or without proprietary additives. Electroplating may also be accomplished from a pyrophosphate bath containing glycine at near neutral 7.5 to 8.5 pH. More work remains to be carried out before this bath can be commercialized. The tin-nickel alloy electroplating is covered under ASTM specification B 605-95a.

PROPERTIES AND APPLICATIONS

Color and Tarnish Resistance

Electroplated tin-nickel has an attractive faint pinkish color. It is resistant to tarnish under both indoor and mild outdoor conditions.

Replacement Coating for Chromium

The hardness of tin-nickel alloy lies between those of nickel and chromium (Table I), and as such it offers an alternative to electroplated chromium for both decorative and protective applications such as in hardware, automotive, electrical, and electronics accessories.

Tin-Nickel Alloy Replaces Nickel Plating on Garment Fasteners

Nickel plating on fasteners is known to be allergic to skin. Tin-nickel alloy is nonallergic. Fasteners for garments have been successfully produced with tin-nickel plating inexpensively.

Frictional and Contact Resistance

The tin-nickel alloy has the ability to retain oil on its surface. This property permits its use in automotive breaking systems, heavy-duty switch gears, mixing valves, and numerous applications involving frictional parts.

Application in Printed Circuit Boards

Tin-nickel alloy finds the following applications in through-hole plating of the printed circuit boards: as an etch resist and as a partial substitute for gold.

Table I. Hardness of Nickel, Tin-Nickel, and Chromium in Vickers Diamond Pyramid Numbers

Plated layer	Nickel	Tin-nickel	Chromium
Hardness, VHN	100–175	600–700	900–1,000

Table II. Solution Compositions for Chloride-Fluoride Baths

Description	*Nonproprietary Bath*	*Proprietary Bath*
Stannous chloride (anhydrous)	50 g/L	50 g/L
Nickel chloride (hexahydrate)	300 g/L	250 g/L
Ammonium bifluoride	55 g/L	—
Ammonium chloride	—	50 g/L
Ammonium hydroxide	To adjust pH	To adjust pH
Proprietary additives	—	20% by volume

As a Diffusion Barrier

A layer of tin-nickel over copper prior to solder (tin-lead) plating prevents the diffusion of copper into the tin-lead layer.

TIN-NICKEL ALLOY PLATING BATHS

Tin-nickel alloy is electroplated mainly from chloride-fluoride bath. It can also be plated from nonfluoride (pyrophosphate) baths but the chemistry for the latter remains to be perfected. The chloride-fluoride bath process is described in detail.

The Chloride-Fluoride Baths

The bath compositions and the operating conditions for the basic nonproprietary and a proprietary bath are provided in Tables II and III.

Chloride-Fluoride Bath Preparation

The fluoride-compatible PVC tank is two thirds filled with water and heated. The required quantity of nickel chloride is dissolved first. Ammonium fluoride is added next. Stannous chloride is added when both the nickel chloride and stannous chloride have been dissolved. Either ammonium hydroxide or hydrofluoric acid may be added to raise or lower the pH respectively. The solution is then filtered through particulate and activated carbon filters and also dummied for 4-6 hours to remove suspended solids and organic and metallic contaminants before putting it to use.

Anodes for Chloride-Fluoride Bath

Both nickel and tin anodes may be used with separate circuits but nickel anodes alone are preferably used. As the tin content of the bath decreases, the deficiency of tin is best compensated with the addition of calculated amounts of stannous chloride salt and the pH adjusted.

Table III. Operating Conditions for Chloride-Fluoride Baths

Description	*Nonproprietary Bath*	*Proprietary Bath*
Stannous tin (Sn^{2+})	25–35 g/L	22–30 g/L
Nickel	60–80 g/L	42–60 g/L
Total fluorine	30–45 g/L	—
Free hydrofluoric acid	4–12 g/L	—
pH	2–2.5	4.2–4.8
Temperature	60–70°C (140–160°F)	50–60°C (120–140°F)
Voltage	1–3	1–3
Cathode current density, A/ft^2	1–30	1–30
Plating rate at 10 A/ft^2	1 μm (40 μ-inches)/5 minutes	1 μm (40 μ-inches)/5 minutes
Solution agitation	Cathode rod movement	Cathode rode movement

Table IV. Defects in Tin-Nickel Plated Alloy and Their Probable Causes

Defect	*Cause*
Cloudy/whitish deposit	Low nickel, high tin, low temperature, organic contamination.
Dark deposit	In low current density areas—due to copper >50 ppm, contamination.
Gray deposit	In high current density areas—due to low tin, low free fluoride, iron >750 ppm and chromium >50 ppm contamination.
Burnt deposit	Low tin content, low temperature, and pH imbalance.
Poor coverage	Excessive iron contamination.
Poor solderability	Deposit passivated and/or aged before soldering.

Bath Agitation and Filtration of Chloride-Fluoride Bath

Agitation is not necessary for very thin deposits but cathode rod movement (mechanical) agitation is employed for thicker deposits. Air agitation is not permitted to prevent oxidation of stannous tin. Continuous filtration is necessary to remove suspended as well as organic matter.

Effects of Process Variables in Chloride-Fluoride Bath

The factors exerting influence on the tin-nickel deposit are the following:

- Very little change in the composition of the deposit with minor variations in tin (stannous, Sn^{2+}) and nickel contents.
- Profound effect in the composition of the deposit with minor changes in the free fluoride content of the deposit. Since fluoride makes a complex with stannous tin, an increase in fluoride content will lower the tin content (percentage) in the deposit and vice versa and accordingly the deposit could be grayish (due to the lack of tin) or whitish (due to the excess of tin) respectively.

Effect of Contaminants in Chloride-Fluoride Bath

- The presence of grease, oil, and organic contaminants will give rise to serious pitting in the tin-nickel deposit.
- The presence of lead over 25 ppm is detrimental, accordingly plating over leaded substrates should be avoided.
- Metallic impurities, such as copper, antimony, iron, zinc, cadmium etc., over 200 ppm are also detrimental, and these must be removed by dummying the solution.

Chloride-Fluoride Bath Troubleshooting Guidelines

Defects in tin-nickel plated alloy are shown in Table IV along with their probable causes.

Nonfluoride (Pyrophosphate) Bath

Where environmental problems exist because of the toxic and corrosive nature of the chloride-fluoride bath, a pyrophosphate bath came into existence. The bath is stated to operate at lower temperature (~50°C, ~120°F) and near neutral (7.5-8.5) pH. Unlike the chloride-fluoride bath, the composition of the plated tin-nickel alloy varies with the contents of individual metals, tin and nickel, in the bath and very little affected with the changes in the pH or the pyrophosphate concentration. The bath composition and the control limits are provided in Table V.

The color of the tin-nickel alloy varies with the tin and nickel contents in the pyrophosphate bath. An excellent application of this bath falls in obtaining gun color from tin-nickel alloy plating. The gun color is accomplished by varying and adjusting the tin and nickel contents of the bath till the desired color is achieved.

Table V. Solution Composition and Operating Conditions for Pyrophosphate Bath

Tin (stannous) chloride (hydrated)	28.2 g/L
Nickel chloride (hydrated)	31.3 g/L
Potassium pyrophosphate (hydrated)	192.2 g/L
Glycine	20 g/L
Temperature	50°C (122°F)
pH	7.5–8.5
Cathode current density	5–15

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ZINC PLATING

by Cliff Biddulph and Michael Marzano

Pavco Inc., Cleveland

The electroplater can achieve excellent results from bright zinc plating electrolytes when the baths are operated correctly. This article is designed to give quick reference to all vital data needed for optimum bath performance. Discussion has been kept to a minimum in favor of tables in an effort to convey more useful information in a simplified form. Present data concentrate on acid chloride zinc, alkaline noncyanide zinc, and cyanide zinc baths. Typical bath compositions are given in Tables I and II.

PLATING TANK CONSTRUCTION

The choice of plating tank construction material should fit the type of bath. All types of tank linings have advantages and disadvantages ranging from length of wear to economy.

Acid Chloride Baths

Acid chloride zinc baths may use fiberglass tanks or polypropylene tanks, but steel tanks must be lined with any of the following: fiberglass, polyvinyl chloride (PVC), or polypropylene. Tanks for chloride zinc must not be constructed of unlined steel.

Alkaline Noncyanide Baths

Alkaline noncyanide zinc baths can use tanks constructed from steel, PVC, fiberglass lined with PVC, or polypropylene. Alkaline noncyanide zinc systems cannot use unlined fiberglass tanks.

Cyanide Baths

Cyanide zinc baths can use tanks constructed of steel, fiberglass, PVC, or polypropylene.

TYPE OF SUBSTRATE TO BE PLATED

The selection of a bath to match the substrate characteristics is of major importance to the success of a zinc plating system. Regular steel substrates and leaded steel substrates both are compatible with acid chloride, alkaline noncyanide, and cyanide zinc systems. In fact, these materials are the only two recommended for alkaline and cyanide plating.

Acid chloride zinc is more flexible in compatibility with other substrates. Successful use on malleable, high-carbon, heat-treated, and carburized substrates can be accomplished with acid chloride zinc systems.

AUTOMATIC CONTROL EQUIPMENT

Automatic control equipment can play an integral role in the operation of a consistent, high-quality plating line. Both acid chloride zinc and alkaline noncyanide zinc systems can benefit from the use of starter, carrier, or refining agent automatic feeder systems. All three


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Table I. Bath Composition

	Zinc Metal[a]	Sodium Hydroxide[b]	Sodium Cyanide	Ammonium Chloride[c]	Potassium Chloride[c]	Boric Acid[d]	pH
Acid Chloride Zinc:							
All ammonium chloride	2.0–4.0			16.0–20.0			5.0–6.0
Low ammonium potassium chloride	2.0–4.0			4.0–6.0	16.0–20.0		5.0–6.0
Nonammonium or all-potassium chloride	3.0–5.0				25.0–30.0	3.0–5.0	5.0–5.5
Alkaline Noncyanide Zinc:							
Low chemistry	0.8–1.2	10.0–14.0					
High chemistry	1.8–3.0	16.0–20.0					
Cyanide Zinc:							
Low cyanide	1.0–1.5	10.0–12.0	1.5–2.5				
Mid cyanide	1.8–2.5	10.0–12.0	3.5–6.0				
High cyanide	3.5–4.5	10.0–12.0	11.0–14.0				

All figures in oz/gal. Conversion to metric: oz/gal × 7.49 = g/L

[a] Zinc metal source:
Acid chloride zinc—zinc chloride.
Alkaline noncyanide zinc—zinc oxide (preferably nonleaded).
Cyanide zinc—zinc oxide or zinc cyanide.

[b] Sodium hydroxide source: mercury cell grade or rayon grade.

[c] Ammonium and potassium chloride source: untreated is preferred.

[d] Boric acid source: granular preferred as powdered form creates a dusting problem.

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Table II. Bath Parameters

	Acid Chloride Zinc	*Alkaline Noncyanide Zinc*	*Cyanide Zinc*
Wetting agents, refining agents or carrier	2–5% by volume	1–3% by volume	Not applicable
Brightener	0.05–0.2% by volume	0.05–0.2% by volume	0.2–0.5% by volume
Temperature[a]	60–130°F	60–110°F	60–110°F

[a] Positive and negative effects are observed when a bath is operated above room temperature (75°F):
1. Because of the solution evaporation, bath buildup problems can be minimized or eliminated.
2. At higher temperatures, higher conductivity means less power consumption.
3. Bath efficiency is higher at higher temperatures. This means less plating time is required.
4. Operating at higher temperatures means savings in refrigeration cost.
5. At elevated temperatures, brightener consumption may be higher than at room temperature.

zinc baths are suited for the use of brightener feeders connected to rectifiers. An automatic pH controller can simplify and improve the operations of an acid chloride zinc bath.

SAFETY CONCERNS

The characteristics of zinc plating baths deserve consideration due to possible safety hazards. While acid chloride zinc and alkaline noncyanide zinc result in no toxicity to humans, cyanide zinc is highly poisonous. Platers should remember that the formulations of acid chloride zinc baths make them corrosive to equipment. Alkaline noncyanide and cyanide baths are noncorrosive to equipment.

Exposure to the chemicals in alkaline noncyanide zinc and cyanide zinc baths can be corrosive to living tissue, whereas acid chloride zinc appears to have little corrosive effect on tissue. Remember to follow all OSHA requirements, checking appropriate material safety data sheets prior to the handling and/or use of all chemicals, whether general or proprietary in nature.

Table III. Miscellaneous Requirements and Properties

	Acid Chloride Zinc	*Alkaline Noncyanide Zinc*	*Cyanide Zinc*
Anode polarization	Seldom	Yes	Yes
Conductivity of the bath solution (higher conductivity lowers energy costs)	Excellent	LC-Poor, HC-Good	Fair
Agitation in rack operations	Required	Not required	Not required
Heating or cooling required	Yes	Yes	Yes
Filtration required	Yes	Yes	Not normally
pH adjustment required	Yes	No	No
Purifier needed to treat impurities	No	Yes	Yes
Chromate receptivity	Good	LC-fair, HC-excellent	Excellent
Waste treatment	Simple	Simple	Complex
Iron treatment by oxidation[a]	Yes	No	No

HC, high chloride; LC, low chloride.

[a] Hydrogen peroxide is most commonly used. When necessary, 20 ml/100 gal of bath is a typical addition. This addition should be diluted with water to a 10% solution before adding. Potassium permanganate may also be used; however, this generates a greater amount of sludge, possibly creating filtration problems and iron precipitation/filtration problems.

OTHER CONSIDERATIONS

Operational requirements for the three types of baths are presented in Table III. Table IV gives a comparison of deposit properties. Troubleshooting is addressed in Table V.

Table IV. Properties of Zinc Baths

	Acid Chloride	*Alkaline Non-Cyanide Zinc*		*Cyanide Zinc*		
		LC	*HC*	*LCN*	*MCN*	*HCN*
Ductility[a] at higher thicknesses	Poor (>0.5 mil)	Poor	Fair/Good	Good	Good	Good
Bath efficiencies	95–97%	70–75%	70–95%	65–70%	70–75%	75–70%
Stardusting	Yes	Yes	Yes	No	No	No
Plate distribution[b]	Poor	Good	Excellent	Good to excellent[c]		
Commercial plating thickness requirements	Excellent	Excellent	Excellent			

HC, high chloride; HCN, high cyanide; LC, low chloride; LCN, low cyanide; MCN, mid cyanide.

[a] Ductility is the ability of a materiality to be bent, molded, or formed without cracking, peeling, or chipping.

[b] Distribution or throwing power is the ratio of the amount of zinc deposited in the current density to the amount of zinc deposited in the low current density.

[c] Plate distribution improves as cyanide to zinc ratio increases.

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Table V. Troubleshooting for Zinc Plating

	Overall Dullness	*HCD Burning*	*Dull LCD*	*Mottled or Blotchy*	*Barrel Perfora- tion Spots*	*Rough- ness*	*Brittle Deposits*	*Pitting*	*Poor Efficiency*
Inadequate agitation	1								
Bath contamination	1,2,3	3,	2	3			2		2
High temperature	1,2,3		1,2,3				3	1	
Low temperature	2	1,2,3	2,3		1		3		1,2,3
High pH	1	1	1		1	1	1		
Low pH		1		1					1
Poor cleaning	1,2,3	1	1	1,2,3		1,3			1
High zinc	2	2	1,2						
Low zinc		1,2							1,2,3
High brightener			1	1			1,2,3,	1,2,3,	2
Low brightener	1,2,3	1,2,3	1,2,3						
Insufficient rinsing	3								
High carrier			1						2
Low carrier	1,2	1	1	1		1	1,2	1	1
High current		1,2,3			1	2,3			
Low current			1						1
Low ammonia		1				1			
Low boric acid		1			1				
Iron contamination		1			1				
Parts too close to anodes		1,2							
Low caustic		2,3	2,3						2,3
Arcing in barrels		3							
High cyanide									3
Low cyanide		3							
Parts burnt in electro		1,2,3							
Hig h chloride				1					
Low chloride			1					1	1
Metallic contamination			1,3					1	
Organic contamination			1,3	1				1,2,3	
Sulfide contamination			2						
Particulates in the bath			2			1,2,3	2,3		
Electrical problems			3						1,3
Chromium contamination				1					
Excessive water hardness				2					
Slow barrel rotation						1			
Magnetized particles						1,2,3			
Low anode area						1,2			1,2,3
Anode sludge						2,3			
Stray current						3			
High ratio							3		
Underpickling			2						1
Overpickling			2						1
Acid drag-in on parts						3			

1. chloride zinc; 2, alkaline noncyanide; 3, cyanide zinc.

(cont. on page 333)

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Table V. Troubleshooting for Zinc Plating (con't)

	Poor Adhesion	*Poor Throw*	*No plate*	*Post-plate Staining*	*Post-storage Staining*	*Falling Zinc Level*	*Rising Zinc Level*	*High Additive Consumption*
Inadequate agitation		2						
Bath contamination		1						2
High temperature		2						1,2,3
Low temperature	2	2	1,2,3					
High pH	1	1				1		
Low pH							1	
Poor cleaning	1,2,3	1,2,3	1,2,3					
High zinc	2	1,2,3						
Low zinc	1							
High brightener	1,2,3	1		1				
Low brightener		2,3						
Insufficient rinsing				1,2,3	1,2,3			
Low carrier	1	1,2		1				
High current	1							
Low current		1,2,3						
Low ammonia	1							
Low boric acid	1							
High caustic							2,3	
Low caustic	2	2				2,3		
High cyanide							3	
Low cyanide		3				3		
Low chloride		1						
Metallic contamination	1			1,2,3	1,2,3			
Organic contamination	1,2							1,2
Electrical problems			1,2,3					
Chromium contamination	2,3		1,2,3					
Too much anode area							1,2,3	
Low anode area	2		1,2,3					
High ratio			3					
Underpickling	1,3	1,2	1,2,3					
Overpickling	1,3	1,2	1,2,3					
Copper in pickle	1,2							
Metallurgical characteristics	1,2,3	2,3	1,2,3					
Current interruptions	1,2							
Nitrate contamination	3							
Excess peroxide added		1	1					
Acid drag-in on parts		3						
Excessive dwell time				1,2				
Bright dip contaminated				1,2,3				
Rinses contaminated				1,2,3				
Improper passivation				1,2,3				
Corrosive environment				1,2,3				
Poor drying and handling				1,2,3				
Poor anode contacts						1		
High drag-in, drag-out						1		2
Anodes polarized						2,3		
Titanium baskets						2		
Low cathode efficiency							3	
Localized chemical adds								1
Improper bright-dip make-up			1,2,3					

1, chloride zinc; 2, alkaline noncyanide; 3, cyanide zinc.

ZINC ALLOY PLATING

by Edward Budman

Chemtech Finishing Systems Inc., Farmington Hills, Mich.

and Robert R. Sizelove

MacDermid Inc., Kearny, N.J.

The application of sacrificial coatings onto steel and other ferrous substrates has long been established as an effective and reliable standard of the industry for corrosion protection. Due to its low cost, zinc has been the predominant coating, although cadmium has also been widely used where zinc fails to provide the necessary corrosion protection for certain applications. Recent demands for higher quality finishes, and, more specifically, longer lasting finishes, have prompted a move to alloy zinc deposits. This has been especially true in the automotive industry, but is also true in the aerospace, fastener, and electrical component fields, among others. Additionally, cadmium users are under increased pressure to stop using it due to its toxic nature.

Several different alloy zinc systems have been introduced, giving deposits of somewhat different properties. The differences come not only from the choice of alloying metal, but from the electrolyte system used as well. Much of the recent research work on alloy zinc electroplating processes was done in Europe and in Japan, where cadmium was effectively outlawed during the 1970s. The alloying elements successfully used with zinc have been iron, cobalt, nickel, and tin. Except for the tin, which is typically an alloy of 70% tin and 30% zinc alloy, zinc comprises from 85 to 99% of the alloy deposit. At these compositions, the deposit maintains an anodic potential to steel, yet remains less active than pure zinc. Analogous to conventional zinc, each of the alloys requires a chromate conversion coating to obtain improved corrosion resistance. Indeed, the chromate in this case is more effective on the alloy deposits than on the pure metal.

ZINC-NICKEL

Zinc-nickel can be plated from acid or alkaline noncyanide solutions. The acid bath typically gives a higher nickel content than the alkaline (i.e., 10 to 14% nickel versus 6 to 9%). Corrosion protection increases with increasing nickel content until approximately 15% is reached. Beyond that level, the zinc-nickel deposit becomes more noble than the substrate, thus losing its corrosion protection properties (see Table I). Additionally, at a nickel content above 10%, the deposit becomes more passive, and, therefore, less receptive to forming a consistent, effective chromate conversion coating. Finally, the deposit from the acidic solution tends to have poor thickness distribution and significant alloy variation from high to low current density areas.

Compared with the acid bath, alkaline zinc-nickel produces a deposit with a lower nickel content, but one that is far more uniform in terms of both thickness of deposit and alloy composition; however, this is done at the sacrifice of plating speed (see Table II). The alkaline bath produces a columnar structure, rather than the laminar structure as deposited from the acidic electrolyte. Thus, the alkaline system maintains better deposit integrity when the part is formed, bent, or crimped after plating. This bath is very simple to operate, being quite similar to conventional alkaline noncyanide zinc processes.

High nickel (10–15%) alloy baths are in use and are specified in the European automotive industry, using alkaline noncyanide technology. Typically, these baths have a

Table I. Bath Parameters for an Acid Zinc-Nickel Bath

Parameter	*Rack*	*Barrel*
Zinc chloride	130 g/L	120 g/L
Nickel chloride	130 g/L	110 g/L
Potassium chloride	230 g/L	—
pH	5.0–6.0	5.0–6.0
Temperature	24–30°C	35–40°C
Cathode current density	0.1–4.0 A/dm^2	0.5–3.0 A/dm^2
Anodes	Zinc and nickel separately. In some cases, separate rectifiers and bussing are required.	

Table II. Bath Parameters for an Alkaline Zinc-Nickel Bath

Parameters	*Amounts*
Zinc metal	8.0 g/L
Nickel metal	1.6 g/L
Sodium hydroxide	130 g/L
Zinc/Nickel ratio	5.0:1
Temperature	23–26°C
Cathode current density	2–10 A/dm^2
Anode current density	5–7 A/dm^2
Anodes	Mix: Nickel-plated iron and nickel-plated steel 70%—zinc 30%

lower cathode efficiency than the low nickel baths. Some electrolytes compensate for this lower efficiency by plating at a slightly warmer temperature. High nickel will cause increased passivity and reduced chromate receptivity as the high nickel acid baths. One main reason for its success is that some major automobile makers specify that the zinc-nickel plated parts must be baked *prior* to salt fog testing. Additionally, higher levels of nickel in the alloy may mean less ductility of the deposit; however, corrosion resistance may increase up to double that of the low nickel baths. Chrome passivates must be more aggressive in order to form a protective film on the deposit. The European community is working towards trivalent chrome passivates, with supplemental topcoats, thus eliminating hexavalent chromates.

Zinc-nickel has consistently achieved the highest corrosion protection as shown by accelerated corrosion testing, with the exception of the SO_2 (Kesternich) test, which favors tin-zinc and zinc-cobalt. Zinc-nickel does, however, retain high corrosion resistance after forming of parts, such as fuel lines, or after heat treating of fasteners and other parts. The ability to continue to deliver good corrosion properties after heat treating has, in some cases, allowed parts to be baked after chromating, rather than before chromating, eliminating the need for double handling.

Adhesion of chromate onto zinc alloy plating is superior to zinc. This comes from an "anchor function" of the second metal. Tin, nickel, iron, and cobalt do not dissolve in the chromate.

Another area where zinc-nickel was found to offer excellent protection is in plating of fasteners that are to be used in contact with aluminum, safely replacing cadmium in this application.

ZINC-COBALT

Commercial zinc-cobalt baths are essentially conventional low ammonium or ammonium-free acid chloride zinc baths, with the addition of a small amount of cobalt. The

Table III. Bath Parameters for an Acid Zinc-Cobalt Bath

Parameters	*Rack*	*Barrel*
Zinc metal	30 g/L	30 g/L
Potassium chloride	180 g/L	225 g/L
Ammonium chloride	45 g/L	—
Cobalt (as metal)	1.9–3.8 g/L	1.9–3.8 g/L
Boric acid	15–25 g/L	15–25 g/L
pH	5.0–6.0	5.0–6.0
Temperature	21–38°C	21–38°C
Cathode current density	0.1–5.0 A/dm^2	1–50 A/dm^2
Anodes	Pure zinc	Pure zinc

resulting deposit is generally up to about 1% cobalt, the balance being zinc. This bath has a high cathode efficiency and high plating speed, with reduced hydrogen embrittlement compared with alkaline systems, but the thickness distribution of the deposit varies substantially with the current density. An alkaline bath is also available (see Tables III and IV for acid and alkaline bath parameters).

Acid cobalt baths have many variables that can affect the cobalt codeposition percentage. These variables include cobalt concentration, zinc concentration, temperature, agitation, pH, current density, and chloride concentration.

Zinc-cobalt deposits will accept blue bright yellow iridescent and nonsilver black chromate conversion coatings.

ZINC-IRON

The primary advantage of zinc-iron is low cost, and an ability to develop a deep uniform black conversion coating from a nonsilver passivate. Additionally, the alloy has good weldability and workability, and can readily be used on electroplated strip steel. It is also used as a base for paint. Of the alloys being considered, zinc-iron will generally give the least improvement in corrosion resistance compared with conventional zinc. If the iron content of the bath gets too high, blistering problems, including delayed blistering, may occur. Corrosion resistance of chromated zinc-iron plated parts drops drastically after exposure to temperatures over 250°F (see Tables V and VI for acid and alkaline bath parameters).

Table IV. Bath Parameters for an Alkaline Zinc-Cobalt Bath

Parameters	*Amounts*
Zinc metal	6–9 g/L
Caustic soda	75–105 g/L
Cobalt metal	30–50 mg/L
Temperature	21–32°C
Cathode current density	2.0–4.0 A/dm^2
Anodes	Steel

Table V. Bath Parameters for an Acid Zinc-Iron Bath

Parameters	*Amounts*
Ferric sulfate	200–300 g/L
Zinc sulfate	200–300 g/L
Sodium sulfate	30 g/L
Sodium acetate	20 g/L

Table VI. Bath Parameters for an Alkaline Zinc-Iron Bath

Parameters	*Amounts*
Zinc metal	20–25 g/L
Iron metal	0.25–0.50 g/L
Caustic soda	120–140 g/L
Temperature	18–23°C
Cathode current density	1.5–3.0 A/dm^2
Anodes	Steel

TIN-ZINC

A number of electrolytes are available for deposition of tin-zinc alloys. These include acid, alkaline, and neutral formulations (see Table VII). In general, an alloy of 25 to 30% zinc with 70 to 75% tin is produced. This range of composition produces optimum corrosion resistance, especially in sulfur dioxide atmospheres, along with excellent solderability (see Table VIII and Fig. 1). As with the other zinc alloys, a chromate conversion coating is required in order to achieve the optimum corrosion protection. In any event, the tin-zinc deposit has good frictional properties, and excellent ductility for use on parts that may be formed after plating; however, being very soft, it is also susceptible to mechanical damage. Electrical contact resistance of the tin-zinc alloy is low, and it is somewhat superior to pure tin for resistance welding of coated mild steel sheet. Additionally, tin-zinc coatings do not undergo bimetallic corrosion, and can be used, for example, on steel fasteners for aluminum alloy panels.

Tin-zinc deposits have good solderability during long periods of storage. This is superior to pure tin. The alloy also does not grow "whiskers" or dendritic crystals for periods to 600 days.

Table VII. Bath Parameters for a Neutral pH Tin-Zinc Bath

Parameters	*Rack*	*Barrel*
Tin	20 g/L	10 g/L
Zinc	8 g/L	10 g/L
Stabilizer	120 g/L	120 g/L
Antioxidant	80 g/L	80 g/L
pH	6.0–7.0	6.0–7.0
Cathode current density	18.5 A/ft^2	5.0 A/ft^2

Table VIII. Sulfur Dioxide Gas Corrosion Test

		Tin-Zinc Alloy Ratio	*Thickness (μm)*	*Hours to White Rust*	*Hours to Red Rust*
Tin-zinc alloy plating	Nonchromated	60/40	10	12	400
		60/40	5	12	210
		75/25	5	9	170
		85/15	5	12	185
	Chromated	60/40	5	20	250
		75/25	5	50	400
		85/15	5	50	250
Zinc plating	Yellow		5	12	200
	Iridescent Chromated		10	12	250

Sulfur dioxide gas concentration, 200–300 ppm; temperature, 40 ±2°C; humidity, >95%.

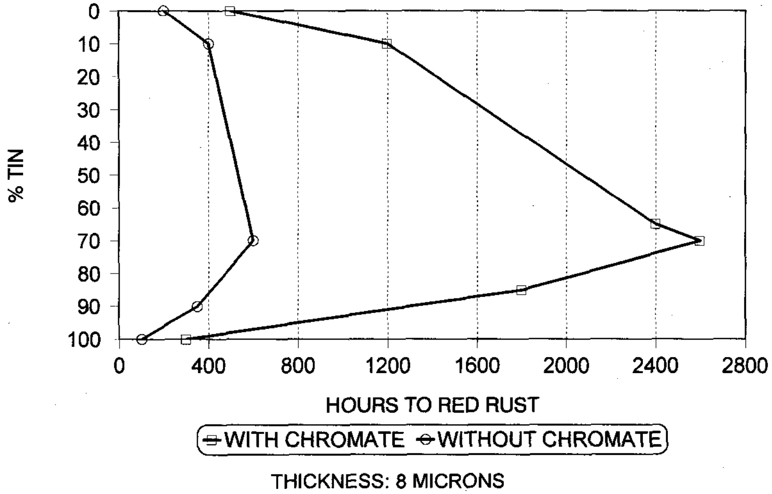

Fig. 1. Corrosion resistance of tin-zinc alloys in salt spray in accordance with ASTM B 117.

CHROMATING

As with conventional zinc or cadmium plating, a chromate conversion coating used in conjunction with the deposit greatly increases corrosion protection compared with a nonchromated surface; however, the presence of the alloying elements affects both the chemistry of the chromate needed to produce an appropriate conversion coating, and the protective mechanism provided by that film. For example, with zinc-nickel, the reaction of the chromating solution on the deposit dissolves some of the zinc from the surface, leaving a nickel-rich layer. This layer provides far superior corrosion resistance than a conventional chromate film. Cost factors previously made tin-zinc the last of the alloy deposits to be considered. Recently, this has changed to where it is in the same range as alkaline zinc-nickel.

HOW TO SELECT A FINISH

Unfortunately, there is no single answer as to the best substitute for zinc or cadmium. Each application must be examined to determine which parameters in the specification are most important. Compatibility of the process with existing equipment may also be a determining factor. For example, an existing acid chloride zinc line may be readily converted to acid zinc-cobalt, if that finish will meet the requirements of the part to be plated; however, if the part is to be heat treated after plating, zinc-cobalt is not indicated as the preferred deposit. An analysis must be made of cost versus quality, and a decision made based on a company's philosophy. Table IX presents data highlighting some of the areas of differences among the finishes described.

CURRENT APPLICATIONS

The United States automotive industry has led the way in the industrial use of zinc alloy plating processes. This mirrors past trends that were first seen in Japan and Europe. Many of

Table IX. Comparison of Zinc Alloy Plating Processes

		Bath Type				
		Alkaline Zinc	*Alkaline Zinc-Nickel*	*Neutral Tin-Zinc*	*Acid Zinc-Nickel*	*Acid Zinc-Cobalt*
Deposit properties	Appearance	Good	Good	Fair	Good	Excellent
	Solderability	Fair	Fair	Excellent	Fair	Fair
	Abrasion	Fair	Good	Poor	Fair	Fair
	Resistance	Fair	Good	Fair	Fair	Fair
	Whisker	Fair	Fair	Good	Fair	Fair
	Ductility			Excellent		
Corrosion resistance		*Chromated*				
	To white rust	Fair	Excellent	Fair	Excellent	Fair
	To red rust	Fair	Excellent	Excellent	Good	Good
		Chromated and Heat Treated				
	To white rust	Poor	Good	Poor	Poor	Poor
	To red rust	Poor	Good	Fair	Poor	Poor
		Chromated and Bent				
	To white rust	Fair	Good	Fair	Fair	Fair
	To red rust	Fair	Good	Excellent	Fair	Fair
Bath characteristics	Throwing power	Good	Excellent	Poor	Good	Poor
	Plating speed	Fair	Poor	Good	Fair	Good
	Covering power	Fair	Fair	Excellent	Fair	Fair
	Bath control	Good	Fair	Fair	Fair	Fair
Analysis and measurement		*Thickness*				
	X-Ray fluorescence	Good	Good	Good	Good	Good
	Coulometric	Good	Good	Good	Good	Good
		Alloy Ratio				
	X-Ray fluorescence	Good	Good	Good	Poor	Poor
	Wet analysis	Good	Good	Good	Fair	Fair
Anodes	—	Separate	Zinc	Alloy	Zinc	Zinc

the first acid baths have yielded to alkaline formulations, which give more uniform alloy deposition and thickness distribution. Some parts that are done are fuel rails and lines, injectors, climate control devices, cooling system pumps, coils, and couplers. Some nonautomotive uses are electric metering parts, power transmission units, maritime, military, aerospace, bearings, and many more. Testing programs are lengthy, due to long-lived finishes. Specification changes are slow, largely due to the enormous cost of changes in rewrites. Zinc alloys have done a creditable job and have earned a well-deserved good reputation.

PLATING PROCEDURES

BARREL PLATING

by Raymund Singleton

Singleton Corp., Cleveland

Barrel plating typically involves a rotating vessel that tumbles a contained, bulk workload. The barrel is immersed, sequentially, in a series of chemical process tanks, including plating baths, while tumbling the workload. Utilizing interior cathode electrical contacts to polarize the workload, dissolved metals are attracted out of solution onto the individual workpieces. Effectively, the workload becomes part of the plating equipment during processing because the individual pieces function as bipolar electrical contacts to the other pieces in the workload. This bipolar contact is a significant contributor to the high efficiencies of barrel plating because the entire surface of the workload, in the current path at any time, is in cathode contact.

USES OF BARREL PLATING

Barrel plating is used most often for bulk finishing. It is the most efficient method for finishing bulk parts and any pieces that do not require individual handling. According to the "Metal Finishing Industry Market Survey 1992–1993,"[1] there are approximately 6,750 plating facilities in the United States. Of these, 37% exclusively provide barrel-plating services, and an additional 32% provide both barrel and rack plating; therefore, approximately 69% of all plating facilities employ the advantages of barrel plating in providing their services.

Plated finishes generally are usually used to deliver the following three functions (singly or in combination): (1) corrosion protection, (2) decoration/appearance, and (3) engineering finishes (for wear surfaces or dimensional tolerances). Barrel plating is used most often for corrosion protection. Because of the surface contact inherent in the tumbling action during processing, barrels are not often used for decorative or engineering finishes.

Advantages

Along with the high efficiency already mentioned, the advantages of barrel plating are many and interrelated:

1. The relatively large cathode contact area yields faster, larger volume production, in the presence of ample current, when compared with rack-type plating.

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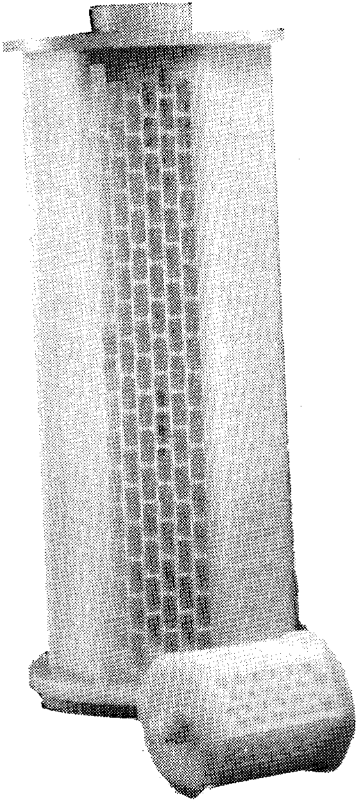


2. A barrel-plating system occupies less floor space and requires a lower investment for equipment than a rack- or other-type plating line of similar capacity.
3. Barrel plating is labor efficient because it is not necessary to handle, rack, load, or unload individual workpieces.
4. The work usually remains in the same vessel for other operations, including cleaning, electrocleaning, rinsing, pickling, chromating, or sealing. A more recent innovation in barrel equipment is drying of the work while it remains in the barrel. The elimination of handling and some work transfer enhances efficiency.
5. Barrel plating is very versatile because of the variety of parts that can be processed in the same equipment. It is the predominant method for finishing fasteners, metal stampings, and similar bulk work. It has been said that "if a part can fit through the door of a barrel, it can be barrel plated." This is an oversimplification. Most often, the part configuration, end use, and finish type determine the applicability of barrel plating.
6. Conversely to barrel operations, rack plating often requires special part carriers or fixturing and other purpose-built equipment. This can include special contacts such as formed anodes based on the individual part type and shape. Barrel plating does not usually require these items, although there are special purpose contacts available.
7. Barrel rotation causes the workload to tumble in a cascading action. This, in addition to the bipolar electrical activity from individually contacting parts, usually produces a more uniform plated finish than rack plating.
8. Agitation of the tank solutions by barrel rotation inherently eliminates stratification and produces homogeneous baths. Additional agitation equipment is usually not required, although certain tanks and operations are equipped with spargers (air agitation pipes).

Origins

Barrel-plating methods originated in the post–Civil War era, with equipment readily adapted from available wooden barrels, kegs, or baskets. Equipment was constructed of wood because it was probably the most economical and available material that was not a conductor of electricity.

Subsequent advances in the knowledge of chemistry, electricity, and material sciences enabled the evolution of barrel-type metal-finishing equipment for bulk finishing. This evolution culminated in the third or fourth decade of the Twentieth Century with now familiar basic designs.

Today, the submerged portions of barrel-plating equipment are constructed, as much as possible, of nonconductive, chemically inert materials that can be utilized in various acid and alkaline solutions. Great advances in plating-barrel performance, capability, and longevity were the result of plastic materials newly available after World War II. Prior to that time, plating barrels were known to be constructed of more primitive plastic or phenolic materials.

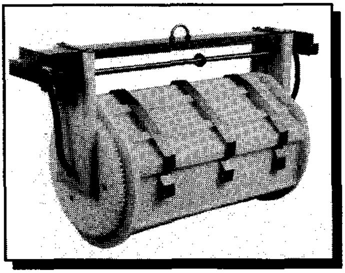
EQUIPMENT TYPES

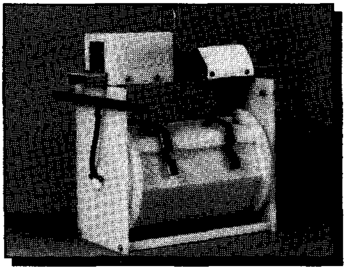
Available barrel equipment varies widely but generally conforms to two major configurations: (1) horizontal barrels and (2) oblique barrels. Horizontal units are the most common, being adaptable to a greater variety and capacity of work (see Fig. 1).

Horizontal barrels also vary by size and are grouped into three major categories: (1) production barrels, (2) portable barrels, and (c) miniature barrels.

Production barrels, the largest units, usually have a capacity in the range of 1.5 to 17 ft^3. They handle the majority of the work.

Portable barrel units are so named because of their generally smaller size (capacities range from 0.1 to 1.5 ft^3) and their ability to be manually transferred from one operation to





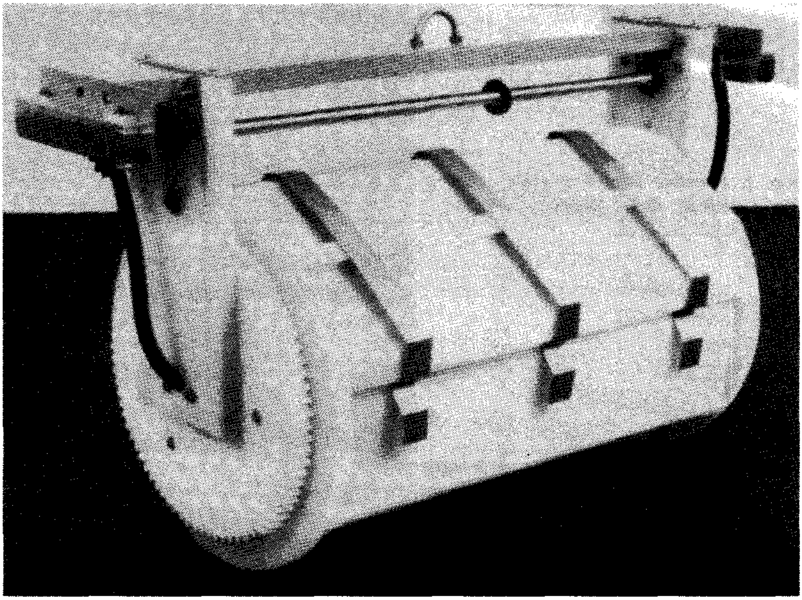


Fig. 1. Typical horizontal barrel and superstructure assembly showing inverted V-type contacts.

the next, sometimes without the aid of an overhead hoist. Portable barrel units are used for plating smaller parts, smaller lots, delicate parts, and precious metals work (see Fig. 2).

Miniature, or minibarrel, units are used for many of the same reasons as portable barrels. Minibarrels range in capacity from 6 to 48 in.^{3} Minibarrels are used to process the smallest and most fragile loads and work. Also, miniature barrels are often used for lab work such as product or process development (see Fig. 3).

Whereas rotation about a horizontal or inclined axis is common to different types and styles of barrel-plating equipment, there are many diverse construction features and components available that enhance capabilities and improve versatility. Examples of these barrel features are as follows:

1. Cylinders with maximized load volumes (see Fig. 1) within the dimensional clearance limits of associated equipment
2. Special-diameter and/or special-length barrel assemblies for use in nonstandardized installations such as rack tanks
3. High-capacity electrical contacts (allowing plating operations with individual barrel assemblies handling as much as 1,400 A per station)
4. Automatic operation for handling, loading, and unloading to reduce labor requirements (see Fig. 4)
5. In-the-barrel drying equipment to dry the work while it remains in the barrel, which reduces parts transfer and handling operations
6. Up-rotation apparatus to minimize contamination and carryover (drag-out) of solution to adjacent process tank stations

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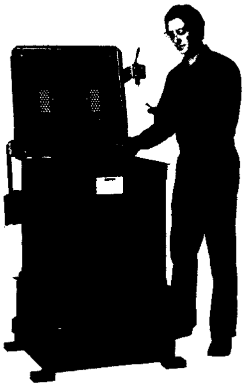

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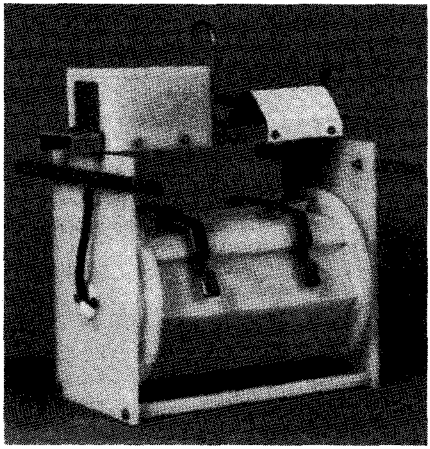

Fig. 2. Portable barrel assembly with self-contained drive, dangler contacts, and clamp-style door.

7. Special apparatus to spray rinse work while it remains inside the barrel to reduce water usage and ensuing treatment costs.

The previous examples are representative. There are other barrel and system enhancements that increase production and reduce cycle times, drag-out, and maintenance requirements. Optional equipment types are many, including the examples of barrel assemblies manufactured to operate in existing rack-plating installations shown in Figures 5 and 6.

Another type of production barrel is the horizontal oscillating barrel. These often utilize barrels that are open on top and have no doors or clamps. The technique is to limit barrel

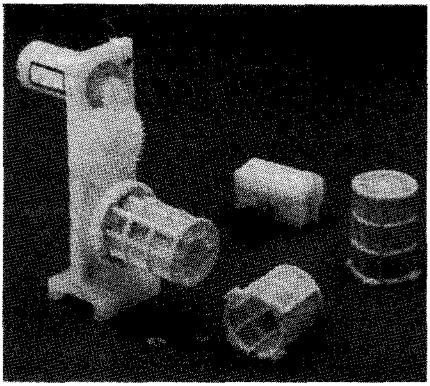

Fig. 3. Ministyle barrel assembly with self-contained drive and integral-mesh, molded baskets.

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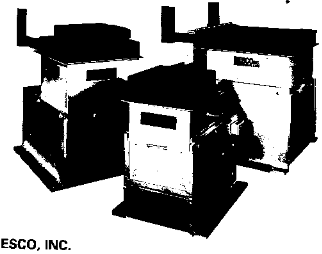

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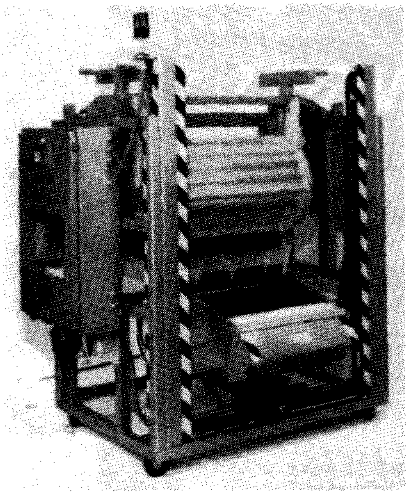

Fig. 4. Fully automatic load/unload system with integral door barrel assembly for hands-off operation.

motion to a back-and-forth (usually less than 180° of arc) rocking action about the horizontal axis, rather than 360° full rotation. The motion is more gentle for very delicate parts and can be a plus when treating parts that tend to nest, tangle, or bridge badly inside the barrel. Because agitation and tumbling are not as vigorous as full rotation, the plater must take care to avoid nonuniform plating (particularly for parts that tend to nest). Processing is generally limited to smaller loads with these barrels to avoid spillage and loss because of the always open door.

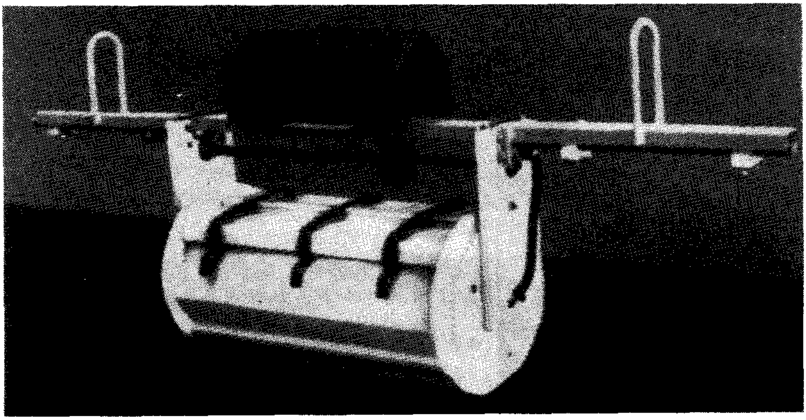

Fig. 5. Barrel assembly equipped for use in a rack plating line.

Oscillating barrels are not utilized as much as they were in the past. This is because platers can use variable-speed drives to produce slower rotational speeds on full-rotation barrels to obtain equivalent results. Many older oscillating barrel installations have been converted to full-rotation operation.

The second major barrel equipment style is the oblique barrel. It can be pictured as an open-top basket that rotates around an axis tilted to a maximum 45° from the vertical. Capacity diminishes beyond a 45° axis tilt.

The major feature of oblique barrels is the elimination of doors or other closure devices. Because the top is open, unloading consists of raising the barrel about a pivot at the top of its rotational axis shaft to a position that dumps the workload. Similar to 180° horizontal oscillating barrels, this results in relatively small workloads and reduced tumbling action. Today, platers can take advantage of fully automatic doors on full-rotation horizontal barrels to achieve the same advantage with greater ease and higher production.

FINISH TYPES

All common types of plating are done in barrels, including zinc (alkaline and acid in various chemical systems), cadmium, tin, copper, precious metals (such as silver and gold), and nickel (both electrolytic and electroless). Barrels are used to plate chrome where ample current and continuous contact are available (gentle abrasion of the part surface is not a problem). One can infer from the previous example that a barrel's value and versatility depend on its capability to (1) plate a particular finish and (2) function properly in system solutions and temperatures. This capability is determined by the materials, construction, and detail features incorporated into the barrel unit.

Some barrel equipment lines have the capability to produce more than one plated metal or finish type. Most plating lines are dedicated to one finish type. Elimination of drag-out in a plating line that produces more than one finish type is a primary concern. Drag-out or cross-contamination of the different plated metals in stations used for rinsing, sealing, chromating, and cleaning can be minimized by incorporating an up-rotation sequence in the barrel operation. Up-rotation is discussed in the section "Hoist systems, tanks, and ancillary equipment."

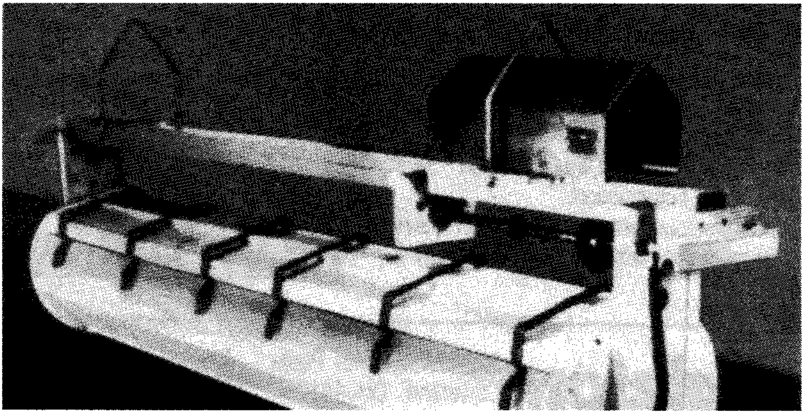

Fig. 6. Special-length barrel assembly for plating elongated parts or for use in a rack plating line.

WORKLOAD

The barrel plater needs to evaluate each of the following items to decide if the desired finish on a particular part can be barrel plated: finish function (relative to use of the part), part configuration, part size, part weight, calculated part surface area, and total workload volume and square foot surface area.

The workload capacity is usually 40 to 60% of the total interior barrel volume. The maximum workload volume is usually determined based on total square foot surface area of the load and the capacity of the bath chemistry and electrical equipment to plate. Other factors are the weight of the individual workpieces and their propensity to damage the finish or serviceability of other parts in the load. Damage of this type is usually the result of the weight, configuration, or edge characteristics of the parts as they tumble in the barrel.

As designated in the section about the uses of barrel plating, plated-finish functions are of three basic types: corrosion protection to increase the useful service life beyond performance of the unplated base material; decoration for appearance, which also enhances the value of the base material; and engineering applications to attain (add material) or maintain a dimensional requirement and/or as a bearing surface.

There are requirements for plated finishes that need to perform more than one of the previously mentioned three basic functions. Barrel plating is most commonly used to finish parts for corrosion protection. Decorative finishes are successfully barrel plated when surface effects from part contact are controlled to an acceptable level. Engineering finishes are not usually applied by barrel plating.

Configuration of the workpieces affects the ability of work to be successfully barrel plated. Generally, parts that weigh less than 1 lb each and are less than 25 $in.^3$ each in volume can be barrel plated successfully. A simple shape is obviously easiest to barrel plate. Barrel plating is usually the most successful, cost-effective way to plate threaded parts and fasteners properly. The tumbling action of the barrel makes and breaks the electrical contact throughout the workload, yielding the most even coverage on the root, mean diameter, and crest of the threads.

Part material must not be adversely affected by any baths required in the total plating-process cycle. A trial load is a useful tool for evaluating which barrel equipment and technique can be utilized for plating a particular part.

Long workpieces and entangling parts, such as rods, bars, or tubes, can be successfully barrel plated. Methods used to plate these parts include long barrels; longitudinal and radial compartments; rocking motion; and various, special stationary contacts (see Fig. 4). Special extra-length barrels allow long parts to fit, whereas compartmented barrels confine movement of long parts and entangling parts, helping to eliminate bridging or entanglement. Limited barrel oscillation or rocking motion (usually 180° of rotation or less) accomplishes the same task by minimizing part movement. To do this a reversing switch, or contactor, along with an adjustable control timer can be installed on the barrel drive to rotate alternately the cylinder in each direction.

The barrel interior can be equipped with stationary cathode contacts to plate small, delicate, or nesting parts (for example, small electronic components with projecting fingers). Stationary contacts rotate with the cylinder so that there is little relative movement between the workpieces and the contacts. As a result, the work cascades over or around the stationary contacts, and less abrasion or edge contact takes place, minimizing the potential for damage to the work (see Fig. 7). Disk, center bar, cup, strip, button, hairpin, and chain are some types of stationary contact. Certain types of stationary contacts, such as strip contacts, assist tumbling of the work.

Parts that are flat or lightweight should be plated in barrels with uneven interior surfaces that are not flat and smooth. A convoluted or uneven barrel interior surface, such as grooved, ribbed, or dimpled, promotes tumbling and eliminates much of the sticking of flat workpieces.

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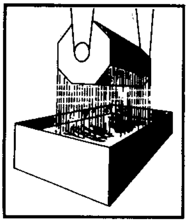

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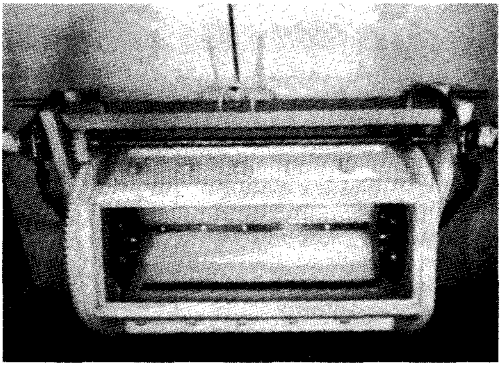

Fig. 7. Barrel interior showing disk- and strip-type contacts.

When finishing recessed or cupped parts, other smaller parts, which are to be plated to the same specification, may be mixed in with the load to provide contact into recessed areas; however, the cost of the time spent to separate the smaller parts from the others after plating must be acceptable.

BARREL EQUIPMENT DESIGN

All designs of barrel equipment, including horizontal and oblique, should include features to optimize productivity. Reduction of labor requirements and improved ease-of-maintenance are important factors for well-designed components and systems. Some of these important features are discussed in the following sections.

Barrel Construction

Barrels should be made of materials that are chemically and physically inert to use in each bath or piece of equipment in the plating line. It is important that the barrels be capable of operation in excess of maximum bath temperatures in the entire system.

A plating barrel may expand and contract as much as 3/8 in. total in length due to the different bath temperatures in a plating line. Changes in temperature cause stresses that can work a barrel to pieces. This is particularly critical for barrels constructed of materials with different coefficients of expansion. The effects of the temperature changes can be minimized with good design and quality construction. When barrels are fabricated of a single type of plastic and joined by a plastic weld or fusion process, stress points are eliminated. Barrels made this way can expand and contract at a uniform rate, which greatly extends their useful service life. The use of metal fasteners for assembly is a less desirable method because of stress points and the possibility of loosening. Minimizing the effects of temperature changes promotes barrel integrity and long life. The capability of a barrel to be used in higher temperature baths can, as an added benefit, aid faster plating.

Good equipment design will reduce maintenance and replacement part costs. Costs are reduced significantly when it is possible to replace individual wear parts and components. Wear parts that are manufactured as an integral piece of a larger components, to reduce manufacturing costs, should be avoided. Examples are (1) trunion hub–bearing surfaces molded as a component of hanger-arm supports and (2) cylinder ring or bull gears that are also the barrel head. These perform the same as other equivalent parts when new, but when the wear part needs to be replaced, the larger piece, of which the wear part is a component, must be replaced. This can be a very costly for the user.

Detail Features

For the majority of plating, flat-sided barrels are best. Flat-sided barrels produce pumping action as a benefit of rotation. Pumping action is the inherent agitation of the bath caused by rotation of the flat-sided barrel. Round barrels do not produce pumping action as efficiently. Pumping action helps constantly replace metal-depleted solution from inside the barrel with fresh solution from the rest of the bath.

Flat-sided barrels tumble parts more effectively. This tumbling is optimized when the flat interior surfaces of the barrel are not smooth. They can be ribbed, grooved, or dimpled. The various types of uneven surfaces also minimize sticking of parts to the panel surfaces, as mentioned previously. Additional tumbling ribs, cross bars, or load breakers of various types are usually needed only for round-plating barrels. They can be added to flat-sided barrels for difficult situations. Most oblique type barrels incorporate uneven, stepped, bottoms to produce these same effects.

Perforations

The type of work being processed in a barrel must be considered when specifying the perforation sizes. Job shops generally use barrels with smaller perforations to accommodate the widest range of potential workpiece sizes. Captive shops often have the luxury of using barrels with larger holes because they can more easily predict their minimum part size. Larger perforations usually exhibit faster drainage, more efficient exchange of metal-depleted solution, and less drag-out (carryout) contamination of adjacent tank solutions. This is because larger perforations minimize the negative effects of liquid surface tension.

Many shops maintain extra barrel assemblies that have the smallest perforation sizes that will be needed. In this way, the line can be operated, the majority of the time, using larger hole barrels. The smaller hole barrels are used only when necessary.

It is very important that all barrels used in a single production line have the same open area ratio, regardless of perforation size. The open area ratio is defined as the total number of holes in a barrel panel multiplied by the individual open area of each hole and divided by the total area that contains the included perforations.

$$\text{Open Area Ratio} = (\text{No. of holes}) \times (\text{Open area of each hole})/\\ \text{Total area for included perforations}$$

For example, if you count 133 holes, 3/32 in. in diameter (0.0069 in.^{2} each), in a 4 in.^{2} area, the calculation would be as follows:

$$\text{Open Area} = 133 \times 0.0069/4 = 0.23 \text{ or } 23\%$$

Interestingly, there is a convenient geometric relationship between hole size, center distance from hole to hole, and open area. When the distance between centers of given diameter holes is twice the diameter of the holes (in a staggered center pattern that has six holes equidistant all the way around), the open area ratio is 23%. Consequently, ⅛ in. diameter holes on ¼ in. centers, 3⁄16 in. diameter holes on ⅜ in. centers, and 1⁄16 in. diameter holes on ⅛ in. centers are all 23% open area ratio patterns. Experience indicates the 23% open area ratio optimizes barrel strength and plating performance.

Because the open area of any barrel determines the access of the plating current to the work, the plating performance is directly related to the percentage of open area; therefore, barrels with the same open area ratio can be used in the same plating line regardless of hole size. Because the access of the plating current to the work will be the same, there is no need to readjust rectifier settings or current density. Most barrels are or should be manufactured with a 23% open area.

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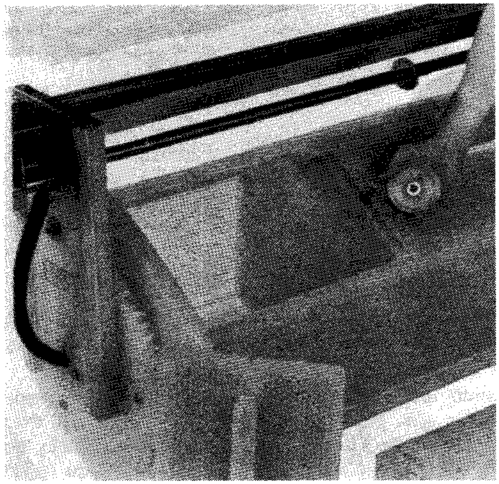


Fig. 9. Knob-style, two-section door with center bar and partition.

Danglers can be ordered with contact knobs made of stainless steel, titanium, or other materials. This is important when the mild steel knobs of standard danglers would be negatively affected by the type of plating chemistry used. Be aware that the alternate materials will probably exhibit lower conductivity.

Other cathode contact types such as disk, cone, center bar, strip, and button contacts will usually do a better job of plating rods, long parts and delicate parts. These types of cathode contacts are referred to as stationary because they are affixed to the barrel itself and rotate with the load. They are, therefore, stationary relative to the load. Stationary contacts are less abrasive to the work and generally exhibit less problems with entanglement. A plate-style contact is usually utilized in oblique-style barrel equipment.

Barrel Doors

There are several available styles and fastening methods for plating-barrel doors. Clamp-style doors have predominated over the years. This is because they are both quick and easy to operate. Knob-style doors are also greatly utilized (see Fig. 10). The threaded components of knob doors must be designed for efficient operation and useful service life to minimize replacement. Divided doors can be furnished for ease of handling because they are smaller, being one half of the total barrel length each. Divided doors are used with partitioned barrels that have a transverse divider in the middle for compartmentalization.

There is, as in all things, diversity in barrel equipment and door operations. Many shops use and prefer clamp-style doors. Clamps are efficient because of quick installation and removal. Others operate successfully with knob-style doors. Many shops use more than one style barrel and door.

Because barrel-door security for part retention and efficient mounting, fastening, and opening of barrel doors is critical to operation of the entire line, much attention is given to this area. Some recent door designs secure the workload within capturing edges of the door opening, rather than from the outside. With this type of design, the door carries the weight of the workload on the capturing edges, rather than the retaining clamps or knobs. This type of design is good for very small parts or workpieces that cumulatively pry and wedge into crevices.

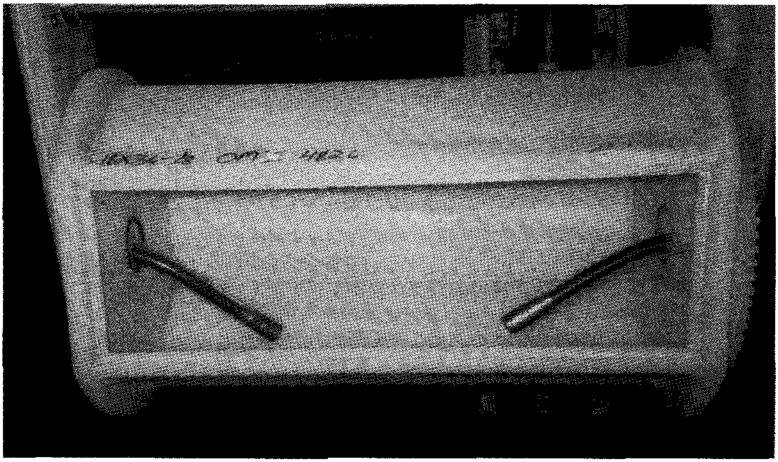


Fig. 10. Dangler-style interior barrel cathode contacts.

Recent innovations to automate operation of plating barrel doors can be utilized to eliminate manual labor for opening, loading, and closing. In addition to the labor savings, the safety of the overall environment of the finishing operation is increased. Automatic barrel operation translates into system automation, which can greatly enhance efficiency and eliminate costs. Automated barrels, hoist systems, and related material handling equipment can be configured in which the equipment automatically sizes and weighs workloads, loads the barrels, closes the barrels for processing, opens the barrels, unloads the finished work to conveying equipment for further processing or drying (see Fig. 4). This is the ultimate evolution of a barrel-finishing system.

Detail Components

There are important equipment features that substantially affect plating system performance and serviceability. It is very important to consider these items and their benefits when selecting barrel-plating equipment.

Horizontal barrel assemblies equipped with an idler gear will result in fully submerged operation of the barrel, ensuring maximum current access to the work. Fully submerged barrel plating also minimizes any potential for problems with accumulated or trapped hydrogen.

Barrel rotation causes a cascading action of the workload inside the barrel. Because of this, the center of gravity of the workload is shifted to one side of the barrel assembly. Tank-driven, horizontal barrel assemblies equipped with an idler gear offset the center of gravity of the cascading workload to the proper side to best resist the tendency of the rotating tank drive gear to lift the barrel contacts from the tank contact points; therefore, use of an idler gear on the barrel assembly helps maintain good electrical contact between the barrel assembly contacts and the cathode contact saddles of the tank. Conversely, a barrel assembly without an idler gear promotes poor electrical contact because the center of gravity of the workload is shifted to the opposite side and works against holding down the contacts.

Another positive feature is hanger arms made of nonconducting materials such as plastic. Nonconducting hanger arms eliminate treeing, stray currents, and possible loss of plating-current efficiency. (Treeing is the accumulation of deposited metal on the barrel or a component because of stray currents.)

Design simplicity and efficiency of barrel equipment are important for ease of maintenance, particularly for components operating below the solution level. The use of alloy fasteners that are nonreactive to the chemical system in use is especially important for acid-based plating systems such as chloride zinc.

HOIST SYSTEMS, TANKS, AND ANCILLARY EQUIPMENT

It is important to the performance capabilities of a barrel hoist and tank system to review the following items and include the advantageous features where possible.

Most barrel-plating tanks are designed to maintain the solution level approximately 5 in. below the top rim of each tank. At this level, the plating barrels should run fully submerged, eliminating the potential for excess hydrogen accumulation. Operating with a solution level higher than 5 in. below the top rim of a tank can cause the solution to be splashed out during barrel entry or exit, resulting in treatment and clean-up problems and wasted solutions.

Solution loss and adjacent-tank drag-out contamination can also be minimized by equipping the barrel hoist system with up-barrel rotation. A drive mechanism on the hoist rotates the barrel and load in the overhead, above-tank, position, facilitating better drainage before moving to the next station. This is especially helpful when finishing cupped- or complex-shaped parts.

Locating the plating-tank anodes (including anode baskets or holders) in the closest proximity to the barrel exteriors, without allowing mechanical interference, ensures greatest current densities for the workload. Anodes that are contour curved to just clear the outside rotational diameter of the barrels can result in 10 to 20% increase in current density.

For horizontal barrels, vertical adjustment of tank-mounted barrel drives should optimize engagement of the gears. Drives that are adjusted too high will carry the weight of the loaded barrel assembly on the drive gear, resulting in excessive stress on the gear, drive shaft, and bearings. This causes premature wear and failure of these components. Reducer oil leakage is also a resulting problem.

In addition, when the weight of the barrel unit is concentrated on the drive gear and drive shaft, rather than on the plating or electroclean tank saddles, proper contact is not possible. If the drive gear carries the barrel assembly, the contacts are most often lifted out of position.

When a tank drive unit is adjusted too low, poor drive-gear engagement results. Sometimes the driven barrel gear hops across the tank drive gear, and the unit does not turn. This situation not only results in premature gear wear because of abrasion but also in poor plating because of poor electrical contact.

It is best to alternate tank drive rotation in a barrel plating line in each following process station. The advantage of having approximately an equal number of drives rotating the barrels in the opposite direction is to ensure even wear on all drive components (bearings, gears, etc.) and greatly extending contacts dangler service life. Alternate rotation of drives certainly minimizes replacement requirements and downtime.

The teeth of the steel gears on barrel assemblies and tank drives should be greased to enhance service life and fully engaged performance greatly. Displaced grease will not negatively affect the tank baths because the gears are normally located beyond and below the tank end wall.

Barrel drives, whether tank or barrel mounted, can have provision to change barrel rotation speed. This is to allow for change of workload type or plating finish. For example, a lower rotation speed is often better for very delicate or heavy parts to minimize abrasion. A faster rotation speed may be used to produce a more uniform plated finish or more readily break up loads of nesting or sticking parts. Allowing for change of barrel rotation speed maximizes the capability to produce the greatest variety of finishes on a larger variety of parts.

Certain tank drives provide for speed change by using multiple-sheave belt pulleys on the output shaft of the drive motor and the input shaft of the speed reducer. Moving the belt onto other steps in the pulley yields a different speed for each step. Many present-day systems use directly coupled C-flange motors bolted directly to the reducer. The speed-change adjustment capability is achieved electrically through the control panel by using adjustable pots or other type controls.

For a long time, it was thought that process tanks with more than three to five stations should be avoided. This is because smaller duplicate tanks, doing the same process, will allow the plating line to continue in operation if a bath needs to be replaced or one of the tanks requires maintenance. Separate tanks for the same process can be plumbed to each other for uniformity of the baths. Each tank can be isolated with valves, when necessary, for maintenance. Experience has shown, however, that many platers prefer to use single-unit, multistation tanks because the bath is more homogeneous and the temperature more uniform. They schedule maintenance at downtimes and have been able to make emergency repairs in a short time, when necessary, in order not to interrupt production.

NEW DEVELOPMENTS

There are at least two notable developments in barrel-system capabilities. As the industry moves toward minimizing water usage and treatment costs, rinsing and drying are receiving attention as operations that can be modified to provide savings.

In-the-barrel drying eliminates labor needed for transfer of the work from the barrel to the dryer basket, loading and unloading of the dryer. When equipment is provided to dry the work in the barrel, work flow is more efficient. The plater must, however, consider the type of workpieces because some do not lend themselves well to in-the-barrel drying. Adequate air flow through the load may not be possible for some types of work. This is particularly true for workpieces that tend to nest together, reducing air circulation. Also, some parts and finish types can be negatively affected when they are tumbled in the dry condition.

Benefits from minimizing water usage and wastewater-treatment costs have caused equipment suppliers to develop an apparatus to use less water in the barrel system.

One development is to connect separate rinse tanks from different parts of the line together, in sequence of descending water quality, to optimize the use of the water before it is sent through filtration and treatment process. In other words, the water is taken advantage of for more turns, and less water is added to the rinse tanks, in total. Of course, not all rinse tanks can be handled together this way because cross-contamination could affect some steps in the finishing process. For where it is practicable, the water savings can be significant. For example, acid rinse baths can be further utilized for the cleaning rinses, as the next step after the cleaning stations is normally the acid dipping or pickling. Also, the acid rinses have a neutralizing effect on the cleaning rinses.

Another technology to minimize water usage is the application of spray rinsing equipment rather than an immersion rinse. Water manifolds with spray nozzles directed on the outside of the barrel wash the barrel and contained workload. Sometimes the barrel is rotated, tumbling the work, while being sprayed. It is expected that water usage is reduced. This method is not effective for all types of work, an example being cupped parts or convoluted workpieces. Another type of spray rinsing equipment incorporates an interior manifold in the barrel and water connection equipment on the outside of the barrel to spray directly onto the work inside the barrel for rinsing. Again, water conservation is the goal for which this equipment has been designed.

RATE OF PRODUCTION

Reasonable production may be maintained with total workload surface area ranging between 60 and 100 square feet per single barrel. Amperage settings can vary substantially with the type of plating. Most production barrel platers operate in the 15 to 40 A/ft^2 range. Nickel plating can vary to 50 A/ft^2. Take note that actual current density is higher because only the exposed surface of the workload in the direct path of the current at any time is plating. The exposed surface is much less than the total calculated surface of the entire load. All surfaces eventually receive the same relative exposure due to the tumbling action in barrel plating.

Barrel tanks generally draw higher amperages than still (rack) tanks of the same capacity; therefore, it is important equip barrel tanks with greater anode area, usually in a 2 to 1 ratio to the total surface area of the workload. Barrel anodes corrode faster than rack-type plating anodes; however, the production is much greater than for a rack-type line.

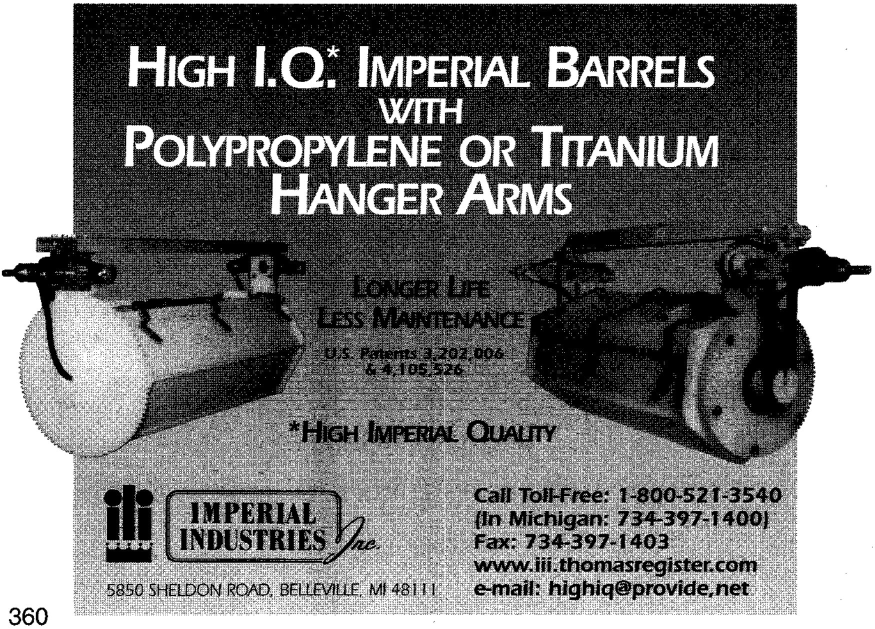
There are references located elsewhere in the *Metal Finishing Guidebook* that permit estimating the time required to deposit a given thickness for many types of plating. There is also information for selecting proper current densities and total cycle times.

RECORDS

Proper operation of a barrel-plating line requires the maintenance of records for each part and plating specification done in the shop. The data can be entered on file cards or in a computer database and used to construct graphs or tables for thickness, time, area, and current relationships. Using the graphs or tables, a plater can make reasonably accurate initial judgments for processing new or unfamiliar work. Suggested items to record for each job include material, part surface areas, part weight, finish type, thickness required, current, and voltage used, as well as load size and plating time.

SUMMARY

Barrel plating has distinct advantages: the ability to finish a larger variety of work and producing a greater volume of work for a specified time period over a rack-type finishing line. By incorporating as many aspects of the previously mentioned information as possible, the capacity and capability of a barrel finishing production line can be optimized.



SELECTIVE ELECTROFINISHING

by D.L. Vanek

SIFCO Selective Plating, Cleveland

Selective electrofinishing encompasses a growing list of portable electrochemical processes. This includes the well-known brush or selective electroplating systems that are used for on-site electroplating, as well as portable anodizing and electropolishing systems. All of these systems are set apart from traditional finishing processes because they are portable. In most cases, selective electrofinishing operations are performed using hand-held tools or anodes.

Selective electrofinishing operations, in their simplest forms, resemble painting. The operator soaks or dips the tool in a solution and then brushes or rubs it against the surface of the material that is to be finished. The tools are covered with an absorbent material that holds solutions so they can be applied to the work surface.

A portable power pack provides a source of direct current for all the processes. The power pack has at least two leads. One lead is connected to the tool and the other is connected to the part being finished.

The direct current supplied by the power pack is used in a circuit that is completed when the tool is touching the work surface. The tool is always kept in motion whenever it is in contact with the work surface. Movement is required to ensure a quality finish.

Work surface preparation is usually accomplished through a series of electrochemical operations. These preparatory steps are performed with the same equipment and tool types that are used for the final finishing operation. Good preparation of the work surface is as important as movement of the tools to produce a quality finish.

DEVELOPMENT

All selective electrofinishing systems evolved from traditional tank finishing processes. Some of the equipment and terms used in these portable processes still resemble their counterparts in tank processes; however, tools, equipment, and solutions cannot be used interchangeably between portable and tank systems.

Because it is more difficult to control temperature and current density in portable finishing processes than in tank processes, there is a need for complete, integrated portable finishing systems for commercial applications. These systems have been developed and are being improved so that they can be used by operators who are not familiar with tank finishing techniques.

Today, selective electrofinishing systems are available for electroplating, electropolishing, anodizing, hard coating, corrosion protection, and decorative applications. These systems, now marketed internationally, vary in degree of sophistication and capability.

Small pencil-type systems apply only flash deposits on small areas. Sophisticated systems use power packs with outputs up to 500 A, and are capable of producing excellent quality finishes over a wide range of thicknesses and characteristics on large surface areas.

ACCEPTANCE

In 1956, the first North American commercial specification was issued for brush electroplating. This formal recognition of a portable process as a viable alternative to tank processes was an important milestone in the development and acceptance of selective electrofinishing processes. Government specifications, MIL-STD 865 (Air Force) and

Table I. Specifications for Selective Electrofinishing Processes

MIL-STD 865	Selective (Brush Plating) Electrodeposition
MIL-STD 2197(SH)	Brush Electroplating On Marine Machinery
AMS 2439	Selective (Brush) Nickel Plating, Low Stressed, Hard Deposit
AMS 2441	Selective (Brush) Nickel Plating, Low Stressed, Low Hardness Deposit
MIL-A-8625	Chromic (Type I), Sulfuric (Type II), Hard Coat (Type III) Anodizing

NAV-SHIPS 0900-038-6010, were issued in 1969 and 1970, respectively. With over 100 commercial specifications now documented for brush plating alone, it is clear that selective electrofinishing processes have gained widespread acceptance.

Specifications have been prepared by manufacturers of electric motors, dies and molds, ships, aircraft, railroads; petrochemical, chemical processing, printing, paper products, and and power generation and transmission products, among others.

The specifications listed in Table I are representative of the current acceptance of selective electrofinishing processes.

EQUIPMENT AND MATERIALS

Selective electrofinishing equipment includes power packs, solutions, plating tools, anode covers, and auxiliary equipment. The proper selection of each item is important in achieving optimum finishing results.

Power Packs

Power packs rectify alternating current to produce a direct current supply. Power packs specifically designed for selective electrofinishing have several features that set them apart from rectifiers used in tank finishing operations.

Power packs are durable and portable. These attributes are necessary because the power packs are routinely transported to the work site. This may be from plant to plant or to various locations within the same plant. The power packs are often equipped with detachable doors to protect their meters and controls while they are in transit or in storage.

Selective electrofinishing power packs have higher maximum output voltages than tank rectifiers, usually about 25 V under full load. This is important because some solutions require an unusually high voltage to achieve required high current densities.

Power packs have forward–reverse current switches. These switches allow the direction of direct current flow to be changed quickly. This is necessary because the combination of preparatory steps and a final finishing step usually requires several rapid changes in the direction of current flow.

These power packs incorporate several safety devices such, as fast-acting circuit breakers, which minimize damage in case the anode, handle, or lead accidentally comes in contact with the work surface, causing a short circuit and arcing.

Power packs have several analogue or digital meters. A voltmeter monitors the initial voltage adjustment for each step in a finishing procedure. An ammeter displays the amperage for each step as it is being carried out. This allows the operator to make adjustments to the current density during the preparatory or plating operation. A precision ampere-hour meter provides data to accurately control the thickness of an electroplated deposit or anodized coating.

Selective electrofinishing power packs have a variable transformer. This allows the output voltage to be adjusted from zero to the maximum output voltage in a continuous manner, instead of in incremental steps. This is necessary because a fraction of a volt or ampere can sometimes mean the difference between a quality or a poor finish.

Sophisticated portable power packs with built-in microprocessors are available. These include an on-board software program, which prompts the operator to enter all of the data required to accomplish a specific finishing operation. After the data are entered, the microprocessor performs a series of calculations and displays the process steps, as well as all the information, such as voltage and amperage settings, needed for the finishing operation.

A variety of power packs designed for selective electrofinishing is commercially available. These power packs are calibrated in accordance with MIL-STD 865. Low amperage output power packs are suitable for finishing small areas. Finishing time requirements for large work surfaces can be reduced by using larger power packs.

Solutions

Selective electrofinishing solutions can be divided into three groups according to their use. Refer to Table II, which lists commonly used solutions.

The first group contains solutions that are used to prepare various types of base materials for finishing. As the name suggests, preparatory solutions are used prior to the finishing step. They prepare the surface so that the finishing step, whether it is brush plating, anodizing, or electropolishing, will produce a quality end product. A quality finish will be evenly colored and distributed on the work surface, and in the case of brush plating will have good adhesion and cohesion.

The selective electrofinishing process referred to as brush plating has preparatory procedures, which have been developed for all of the base materials commonly encountered. These include steel, cast iron, stainless steel, aluminum, copper-base alloys, and nickel-base alloys. When recommended procedures are followed, the strength of the bond between the brush-plated deposit and the base material is equivalent to the weaker of the cohesive strength of the deposit or of the base material itself.

Preparation of a base material usually begins with mechanical and/or chemical precleaning. This is followed by electrocleaning and then etching. Depending on the base material, a desmutting, activating, and/or preplating step may be required. For instance, the procedure for brush plating a copper deposit onto 400 series stainless steel requires all of the steps previously mentioned (see Table III).

The second group of selective electrofinishing solutions consists of those used only in brush plating. Solutions in this group are used for depositing a wide variety of pure metals and metal alloys.

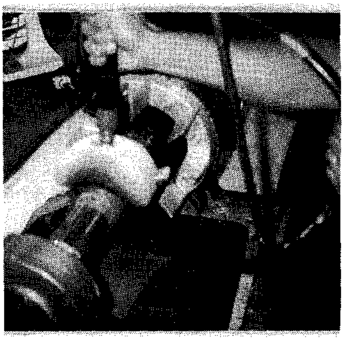
Brush-plating solutions are quite different from tank-plating solutions. Brush-plating solutions have a higher metal content, are less likely to utilize a toxic material such as cyanide, are more likely to use metal-organic salts rather than metal-inorganic salts, and are more likely to be complexed and/or buffered with special chemicals than are tank plating solutions.

Solutions used for brush plating must produce a good quality deposit over a wider range of current densities and temperatures than tank plating solutions. They must plate rapidly, operate with insoluble anodes, and produce a good deposit under variable conditions for a prolonged period of time. In addition, the solutions should be as nontoxic as possible, and they should not require chemical control by the operator. Formulations that are different from those used in tank plating are obviously required to achieve these objectives.

The third group of solutions have been developed to meet the specific application requirements of portable processes such as selective anodizing, specialized black optical coatings, and electropolishing.

Selective Anodizing

Anodizing is a widely used electrochemical surface treatment process for aluminum and its alloys. Depending on the particular type of anodizing process used, the resulting anodic coatings provide improved wear resistance, corrosion protection, and/or adhesive properties for subsequent painting or adhesive repair.



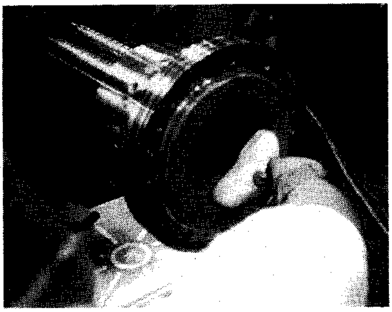


Table II. Solution Types

Group I—Preparatory Solutions:

Cleaning	For most materials
Etching	For aluminum alloys, steels, cast iron, high-temperature nickel-base materials, and stainless steel
Desmutting	For cast iron, carbon and alloy steels, and copper alloys
Activating	For high-temperature nickel-base materials, stainless steel, cadmium, and chromium

Group II—Plating Solutions for Ferrous and Nonferrous Metals:

Antimony
Bismuth
Cadmium (acid)
Cadmium (alkaline)
Cadmium (no bake)
Chromium (dense trivalent)
Chromium (hexavalent)
Cobalt (for heavy buildup)
Copper (acid)
Copper (alkaline)
Copper (neutral)
Copper (high-speed acid)
Copper (high-speed alkaline for heavy buildup)
Iron
Lead (alkaline)
Lead (for alloying)
Nickel (dense)
Nickel (alkaline)
Nickel (acid strike)
Nickel (neutral, for heavy buildup)
Nickel (ductile, for corrosion protection)
Nickel (sulfamate, soft, low stress)
Nickel (sulfamate, moderate hardness)
Nickel (sulfamate, hard, low stress)
Tin (alkaline)
Zinc (alkaline)
Zinc (neutral)
Zinc (bright)

Group II—Brush Plating Solutions for Precious Metals:

Gallium
Gold (alkaline)
Gold (neutral)
Gold (acid)
Gold (noncyanide)
Gold (gel)
Indium
Palladium
Platinum
Rhenium
Rhodium
Silver (soft)
Silver (hard)
Silver (noncyanide)

Group II—Plating Solutions for Alloys:

Brass
Nickel-Cobalt
Tin-Indium
Tin-Lead-Nickel
Cobalt-Tungsten
Nickel-Tungsten
Babbitt Navy Grade 2
Tin-Cadmium
Zinc-Nickel

Group III—Special Purpose Solutions and Gels:[a]

Anodizing (chromic*)
Anodizing (sulfuric)
Anodizing (hard coat)
Anodizing (phosphoric*)
Anodizing (boric-sulfuric*)
Chromate treatment
Electropolishing
Cadmium replacement
Black optical
Metal stripping

[a] Gels are denoted by asterisks.

Selective anodizing is used when limited, selective areas of large or complex aluminum assemblies need anodizing either to restore a previously anodized surface or to meet a specification requirement. Selective anodizing is a versatile tool, which can be used for many different, demanding original equipment manufacturer (OEM) and repair applications. This portable process can be used both in the shop and in the field.

Anodizing is the formation of an oxide film or coating on an aluminum surface using reverse current (part is positive) and a suitable electrolyte. Principal types of anodized

Table III. Copper Plating 400 Series Stainless Steel

Step	*Operation*	*Solution*	*Polarity*	*Objective*
1	Preclean	As applicable	—	Remove any visible films of oil, grease, oxides, paints, etc.
2	Electroclean	Cleaning solution	Forward	Remove last traces of oil, dirt, grease, etc.
3	Rinse	Clean tap water	—	Completely remove previous solution.
4	Etch	Etching solution	Reverse	Remove surface material such as oxides, corrosion, and smeared metal.
5	Rinse	Clean tap water	—	Completely remove previous solution.
6	Desmut	Desmutting solution	Reverse	Remove undissolved carbon smut from surface.
7	Rinse	Clean tap water	—	Completely remove previous solution.
8	Activate	Activating solution	Forward	Remove passive film formed while desmutting.
9	No rinse	—	—	Prevent passivation. Rinsing will repassivate the surface.
10	Nickel preplate	Nickel (dense)	Forward	Direct application of copper would result in an immersion deposit and poor adhesion. The nickel preplate prevents this undesirable result.
11	Rinse	Clean tap water	—	Completely remove previous solution.
12	Electroplate	Copper	Forward	Plate to desired thickness.

coatings are chromic, sulfuric, hard coat, phosphoric, and boric-sulfuric. The process of selective electroplating has been expanded to provide a portable method of selectively applying these anodized coatings for a variety of localized area applications.

The electrolytes used for selective anodizing are available in water-based solutions. Gel electrolytes are available for chromic acid, phosphoric acid, and boric-sulfuric acid anodizing. The gels produce coatings comparable to solution electrolytes and have the advantage of staying on the selected work surface. The gels are ideally suited for work in confined areas where it would be difficult to clean up spills.

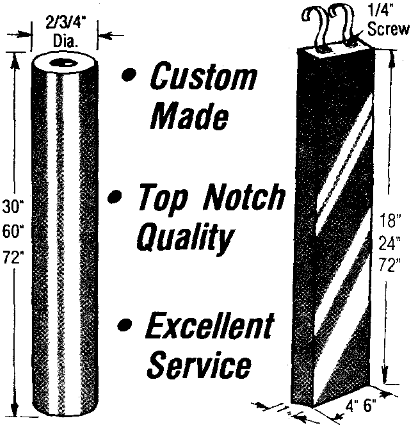
In military and commercial applications, anodized coatings are usually applied for dimensional reasons (salvage), corrosion protection, and/or wear resistance purposes. Selective anodizing meets the performance requirements of MIL-A-8625 for type I, II, and III anodized coatings. In the consumer marketplace, anodizing is often utilized for cosmetic appearance reasons.

The five types of anodizing differ markedly in the electrolytes used, the typical thickness of the coating formed, and in the purpose of the coating. Also, the five types of anodized coatings are formed under distinctively different operating conditions.

The gel is used when anodizing near critical components that may be damaged by splashed or running anodizing solutions. The gel stays over the work area and does not stray into inappropriate places such as aircraft instrumentation, equipment, and crevices where corrosion would start. With the gel there is also less likelihood of damage to the airframe.

Selective Electrofinishing Tools

Tools used in selective electrofinishing processes are known as plating tools, stylus, or styli. They are used to prepare, as well as brush plate, anodize, and electropolish work surfaces. The tools consist of the following elements: a handle with electrical input connectors, an anode, an anode cover, and in some cases, a means of solution flow. Additionally, the tool must have a high current carrying capability and must not contaminate the solution.


2/3/4" Dia.
30"
60"
72"
• Custom Made
• Top Notch Quality
• Excellent Service
1/4" Screw
18"
24"
72"
4" 6"

Only insoluble anodes are used in selective electrofinishing. The reason for this is simple. Products of the anodic reaction would build up on a soluble anode when subjected to the high current densities necessary for selective electrofinishing applications. The reaction products would be contained by the anode cover, resulting in a decrease in current to unacceptable levels. For this reason, soluble anodes are not used.

Graphite and platinum are excellent materials for selective electrofinishing anodes. The purer grades of graphite are economical, thermally and electrically conductive, noncontaminating, easily machined, and resistant to electrochemical attack.

Platinum anodes, although more expensive, are used in some cases. These anodes may be made from pure platinum or from either niobium or columbium clad with platinum. The use of platinum anodes is generally reserved for brush-plating applications that are long term or repetitive, or that require thick brush-plated deposits.

Platinum anodes are also an excellent choice when brush plating bores as small as one-sixteenth of an inch in diameter. Graphite anodes this small in diameter are brittle and are easily broken.

Because selective electrofinishing occurs only where the tool touches the part, it is best to select a tool that covers the largest practical surface area of the part. Selecting the correct tool also ensures uniformity of the finish.

Manufacturers offer a wide selection of standard selective electrofinishing tools. These tools are available in a variety of sizes and shapes to accommodate different surface shapes; however, special tools are frequently made to accommodate special shapes or large areas. Proper design of these tools is critical to successful finishing operations.

An equally important aspect of selective electrofinishing processes is the selection of an anode cover (cathode cover for anodizing or electropolishing). Anode covers perform several important functions. They form an insulated barrier between the anode and the part being finished. This prevents a short circuit, which might damage the work surface. Absorbent anode covers also hold and uniformly distribute a supply of finishing solution across the work surface. The solution held in the anode covers provides a path for the direct current supplied by the power pack. This is required for all selective electrofinishing processes. Anode covers also mechanically scrub the surface being finished.

All anode cover materials sold by manufacturers are screened for possible contaminants. Many materials that seem similar contain binders, stiffening agents, and lubricants that will contaminate finishing solutions. Testing has shown that these contaminants have a significant impact on finish quality and adhesion of deposited materials. Anode covers that are suitable for selective electrofinishing should be obtained from solution manufacturers to avoid contamination.

Auxiliary Equipment

When a finishing operation is required on a large work surface or a deposit is applied in a high thickness, the best results are obtained by continuously recirculating the finishing solution with a simple pump or a flow system. This method will reduce the time required for the finishing process by eliminating lost time from dipping the anode, and by supplying fresh solution to cool the work surface so that higher current densities can be used.

Submersible and peristaltic pumps are used when operating in the 1–100 A range, and when the finishing solution does not have to be preheated. Flow systems, which include specially fabricated tanks ranging in size from 1 to 10 gallons, heavy-duty magnetic drive-pumps and a filter, are used when operating in the 100–500 A range, and when the solution has to be preheated.

The most sophisticated flow systems are used with nickel sulfamate brush-plating solutions because they require preheating and constant filtering. These units have reservoirs of several sizes, pumps designed for high-temperature operation, provision for filtering, and the capability of changing filters while plating. In addition, they include a heater and heater control that preheats and maintains the solution at the proper temperature. Flow systems can also be equipped with cooling units for anodizing and high-current brush-plating operations.

Turning equipment is frequently used to speed up and simplify finishing operations. Specially designed turning heads are used for small parts, i.e., diameter less than approximately 6 in., length less than 2 ft, and weight less than 50 lb. Lathes are often used to rotate large parts while brush plating inside or outside diameters.

When a part cannot be rotated, special equipment can be used to rotate anodes. For bores up to 1½ in. in diameter, small rotary units are used. These have a variable speed motor, flexible cable, and a special handle with rotating anode and stationary hand-held housing. For bores in the 1–6-in. diameter range, larger rotary units are required. These are similar to the smaller ones, but include heavy-duty components and they have provisions for pumping solution through the anode.

The largest turning units are used for bore sizes in the 4–36-in. diameter range. These units have two opposing solution-fed anodes, which are rotated by a variable speed motor. The anodes are mounted on leaf springs, which apply the correct amount of pressure and also compensate for cover wear. These devices are used at up to 150 A. They are not hand-held, but mounted on a supporting table instead.

Traversing arms are used to supply either a mechanical oscillation or a back and forth "traversing" motion for an otherwise manual selective electrofinishing operation.

ADVANTAGES AND DISADVANTAGES

Selective electrofinishing processes are used approximately 50% of the time because they offer a superior alternative to tank finishing processes, and 50% of the time because they are, in general, better repair methods for worn, mismachined, or damaged parts.

For example, the decision to use brush plating rather than tank plating, welding, or metal spraying, depends on the specific application. There are distinct advantages and disadvantages, which should be considered.

Some advantages of brush plating over other repair methods are:

- The equipment is compact and portable. It can be taken to the work site so that large or complicated equipment does not have to be disassembled or moved.
- No special surface preparation, such as knurling, grit blasting, or undercutting, is required. The only requirement is that the surface be reasonably clean. Often, solvent cleaning or sanding the work surface is sufficient.
- Brush plating does not significantly heat the part or work surface. Only occasionally is the part heated to approximately 130°F, and never does the temperature of the part exceed 212°F. Hence, distortion of the part does not occur.
- The process can be used on most metals and alloys. Excellent adhesion is obtained on all of the commonly used metals including steel, cast iron, aluminum, copper, zinc, and chromium.
- Thickness of the plated deposit can be closely controlled. Frequently, mismachined parts can be plated to size without remachining.
- Parts having a wide variety of sizes and shapes can be easily brush plated.

Some disadvantages of brush plating compared with other repair processes are:

- Brush-plated deposits are applied at a rate that is at least 10 times faster than tank plating; however, the rate of deposition is considered to be moderate when compared with that of welding or metal spraying. A fair comparison is not complete unless consideration is given to the quality of a brush-plated deposit and the fact that brush plating often eliminates the need for pre- or post-machining and grinding, which may be required with other repair processes. Because parts can often be plated to size, brush plating provides a finished product in a shorter period of time.
- In practice, the hardest deposit that can be applied in a high thickness with the brush-plating process is 54 R_c. This is not as hard as the hardest deposits produced by

some other processes; however, the other processes do not offer the range of hardnesses or deposit types that can be applied with the brush-plating process.

- Brush plating is usually a superior approach to plating a selected area on a complex part; however, it usually is not suitable for plating an entire part that has a complex shape such as a coffeepot.

QUALITY OF BRUSH-PLATED DEPOSITS

Because brush-plated deposits are applied at much faster rates than those achieved in tank plating, some tank platers are skeptical of the quality of brush-plated deposits. Manufacturers of brush-plating equipment, however, have continuously improved their solutions, procedures, and equipment. Consequently, the results obtained with brush plating can match, and often exceed, the quality achieved with tank plating.

The manufacturers of brush-plating equipment generally offer a number of plating solutions for each of the more important metals. One reason for this is to offer a choice in properties. For example, one user may want a hard, wear-resistant nickel, whereas another wants an impact-resistant, ductile coating. As the ductility of metals, whether wrought, cast, or plated, generally decreases with increasing hardness, it is impossible to meet both requirements with a single solution.

Adhesion

The adhesion of brush electrodeposits is excellent and comparable to that of good tank plating on a wide variety of materials including steel, cast iron, stainless steel, copper, and high-temperature nickel-base materials. When plating on these materials, the adhesion requirements of federal and military specifications are easily met. Limited, but occasionally useful, adhesion is obtained on metals that are difficult to plate such as titanium, tungsten, and tantalum.

Most adhesion evaluations have been made using destructive qualitative tests such as chisel or bend tests. These tests indicate that the adhesion and cohesion of brush-plated deposits are about the same as the cohesive strength of the base material.

Quantitative tests have been run using ASTM Test Procedure C653-79 “Standard Test Method for Adhesion or Cohesive Strength of Flame Sprayed Coating.'' Four samples were plated with a nickel neutral solution. The cement used to bond the plated sample to the testing apparatus failed during the test. Because the adhesive had a bond strength rated at approximately 11,300 psi, it was shown that the bond strength of the plated deposit was at least 11,300 psi. Even brush-plated deposits with a fair adhesive rating survived this test and, therefore, have an adhesive bond and cohesive strength of at least 11,300 psi. Brush-plated bonds are, therefore, stronger than the bonds found with flame-sprayed coatings.

Metallographic Structure

The metallographic structure of an electroplate can be examined in an etched or unetched condition. In the unetched condition, most brush-plated deposits are metallurgically dense and free of defects. Some of the harder deposits, such as chromium, cobalt-tungsten, and the hardest nickel, are microcracked much like hard tank chromium. A few are deliberately microporous, such as some of the cadmium and zinc deposits. Microporosity does not affect the corrosion protection of these deposits, as they are intended to be sacrificial coatings. The microporous structure offers an advantage over a dense deposit because it permits hydrogen to be baked out naturally at ambient temperatures or in a baking operation. Etched, brush-plated deposits show grain structures that vary, but parallel those of tank deposits. Brush-plated deposits tend to be more fine grained. Coarse-grained, columnar structures, such as those found in Watts nickel tank deposits, have not been seen in brush-plated deposits.

Table IV. Comparison of Hardness of Deposits from Tank and Brush Plating

Metal	*Microhardness from Tank Plating*	*D.P.H. from Brush Plating*
Cadmium	30–50	20–27
Chromium	280–1,200	580–780
Cobalt	180–440	510
Copper	53–350	140–210
Gold	40–100	140–150
Lead	4–20	7
Nickel	150–760	280–580
Palladium	85–450	375
Rhodium	550–1,000	800
Silver	42–190	70–140
Tin	4–15	7
Zinc	35–135	40–54

Hardness

The hardness of brush-plated deposits lies within the broad range of the hardnesses obtained with tank deposits. Brush-plated cobalt and gold, however, are harder than tank-plated deposits. Brush-plated chromium is softer, as tank-plated chromium is generally in the 750–1,100 D.P.H. range. Table IV shows the hardness of brush-plated deposits versus the hardness of bath-plated deposits.

Corrosion Protection

Brush-plated cadmium, lead, nickel, tin, zinc, and zinc-nickel deposits on steel have been salt spray tested per ASTM B 117. When the results were compared with AMS and military specification requirements, the brush-plated deposits met or exceeded the requirements for tank electroplates.

Electrical Contact Resistance

Brush electroplates are often used to insure good electrical contact between mating components on printed circuit boards, bus bars, and circuit breakers. A low contact resistance is the desired characteristic in these applications.

Hydrogen Embrittlement

Hydrogen embrittlement testing is expensive and, therefore, only a few solutions have been evaluated. The evidence acquired to date suggests that brush plating offers low levels of hydrogen embrittlement of base metals.

Cadmium and zinc-nickel plating solutions have been specifically developed for plating or touching up high-strength steel parts without the need for a postplate bake.

Hydrogen embrittlement testing over the past 20 years has become progressively more difficult to pass. A no-bake, alkaline, brush-plated cadmium deposit has passed an aircraft manufacturer's test, which is perhaps the toughest imaginable. The test consisted of the following steps:

1. Prepare six notched tensile samples from SAE 4340, heat treated to 260-280 ksi, with a 0.010-in. radius notch.
2. Plate samples with 0.5–0.7 mil cadmium while under load at 75% of ultimate notched tensile strength.
3. Maintain the load for 200 hours.

PULSE AND PULSE-REVERSE ELECTROPLATING

by N.V. Mandich

HBM Engineering Co., Lansing, Ill.

Electroplating with pulse current (PC) and pulse-reverse current (PRC) is a technique where standard, stationary DC current is replaced with its modulated (nonstationary) forms. Although it has been recognized for a long time electroplating with modulated currents was mostly dormant and used only occasionally for PRC plating of cyanide copper where better leveling was recognized early in the 1940s and 1950s.

Lack of appropriate current sources and/or its prohibitive cost hampered the further interest for this otherwise promising technique for the next 4 decades. Although it was known that the morphology of gold and gold alloys would be influenced by periodically reversed or pulsed current, great interest was developed only when it was realized that pulse-plated gold deposits proved superior to DC-plated deposits for certain electronic applications. The age of electronics and materials shortages gave new importance to gold as a commodity, and a boom in gold prices led to a demand for ways of reducing gold consumption.

Pulsing proved to be an answer and this justified the more expensive pulse rectifiers. After that theoretical contributions and industrial applications followed.

GENERAL CHARACTERISTICS OF UNIPOLAR AND BIPOLAR CURRENTS

Before the effect of pulsed current on various aspects of metal deposition is elaborated it is necessary to examine the way in which pulsed current waveforms are characterized. The advent of modern electronics and microprocessor control has permitted great flexibility of the programming of the applied current waveform. Trains of pulses can be programmed to give very complex waveforms. Square waves are the easiest waveforms to produce because this requires only a switching arrangement rather than a specialized waveform generator. Current waveforms can be divided into two major groups: These are unipolar pulses, where all the pulses are in one direction, and bipolar pulses, where anodic and cathodic pulses are mixed. There are many variants on these, but as the complexity of the waveform increases so does the number of variables, which makes it more difficult to understand how a particular waveform affects the electrodeposition process. Consequently, the present discussion is restricted to the consideration of the simplest case of unipolar and bipolar pulses, i.e., pulse and pulse reverse.

In order to characterize a direct current it is sufficient to know the current density. The characterization of a train of current pulses requires three parameters to be known. These are the cathodic peak pulse current density, j_c; the cathodic pulse length, t_c; and the interval between the pulses, t_p, as shown in Fig. 1. In practice average current density, j_{AV}, is measured, and it is expressed in the case of PC as follows:

$$j_{AV} = (j_c \times t_c)/(t_c + t_p) \qquad (1)$$

A quantity frequently encountered is the duty cycle, T, representing the portion of time in each cycle when the current is on. It is defined by the following equation:

$$T = t_c/(t_c + t_p) \qquad (2)$$

The product of the duty cycle and the peak pulse current density gives the PC average current density.

$$j_{AV} = j_c \times T \qquad (3)$$

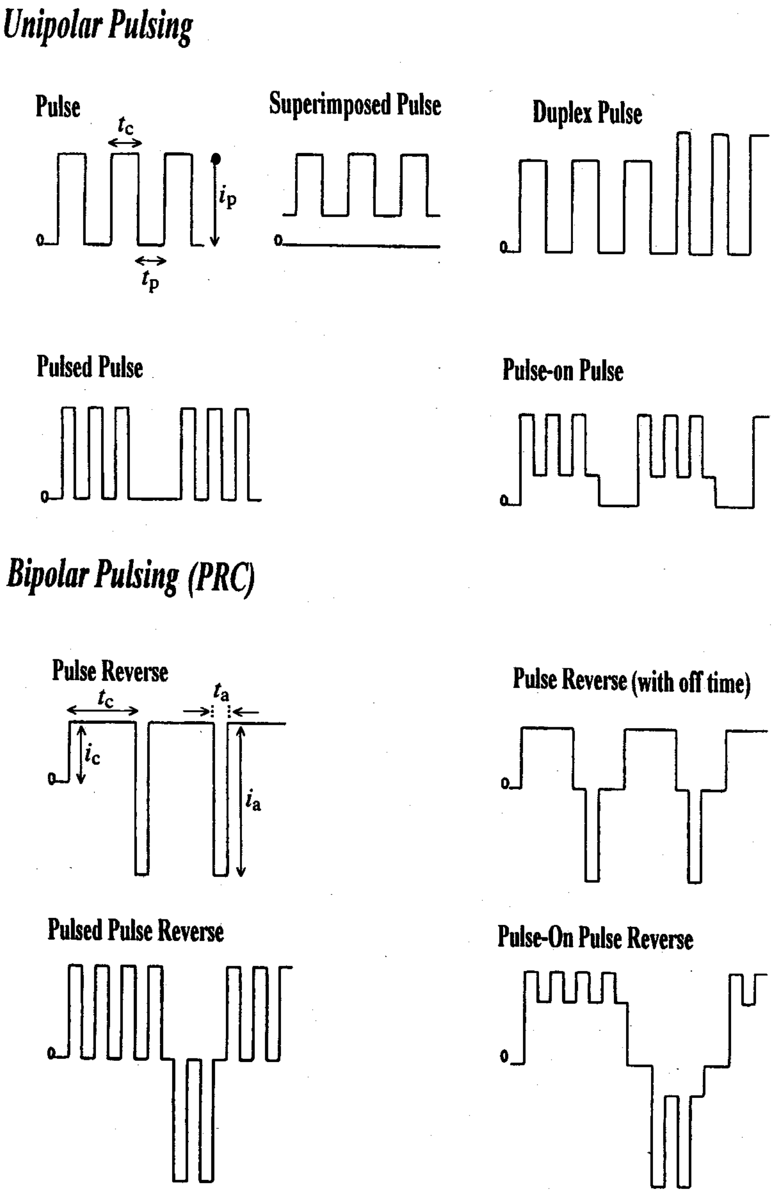


Fig. 1. Nonstationary current waveforms for unipolar and bipolar pulsing.

The characterization of a PRC waveform requires four parameters to be known and defined by the following equations:

$$j_{AV} = (j_c \times t_c + j_a t_a)/(t_c + t_a) \qquad (4)$$

where t_a = anodic pulse time.

$$T_{PRC} = (j_c \times t_c - j_a t_a)\backslash(j_c\ t_c) \qquad (5)$$

where j_a = anodic current density.

THE EFFECT OF PULSED CURRENT ON DEPOSIT PROPERTIES

Unipolar pulsed current justified its practical application mainly through its ability to affect the mechanisms of electrocrystallization, which in turn, controls the physical and mechanical properties of the electrodeposited metal. Because the nucleation rate of a growing electrodeposit is proportional to the applied current density, the use of high current density pulses can produce deposits with reduced porosity and, in most cases, a finer grain size. Whether a finer grained deposit is obtained in practice depends upon what happens during t_p when the current is interrupted because this can allow the desorption of impurities and encourage renucleation with the formation of new, smaller crystal grains. The effects obtained in practice are also dependent on the specific electrochemical system to which a particular set of the current pulses is applied.

A common example of different grain growth caused by the desorption of impurities is observed when current pulses are applied to an acid gold-cobalt alloy plating system. In this case deposits by pulse current have a very low carbon and nitrogen content and the grain size is either decreased or increased depending on duty cycle. There is also a significant increase in the ductility of these deposits and an increase in electrical conductivity and density, as well as a decrease in porosity. Decrease in porosity in practice means that a thinner gold deposit can be applied and still pass porosity tests, resulting in a significant cost saving. Another rather unexpected metal where pulse current plating has found its application is nickel, which was of practical interest due to the ability of pulsed current to control the levels of stress and ductility in nickel deposits. This has some obvious applications in the electroforming industry where stress control is of paramount importance.

LIMITATIONS OF PC IMPOSED BY DUTY CYCLE AND FREQUENCY

The rate of metal deposition is dictated by the average current density and is equivalent to the applied current density in DC plating. Now, the first major limitation of pulse plating from a practical viewpoint becomes evident. In order to produce the same average deposition rate as for DC, as duty cycle is reduced, the peak pulse current density needs to be increased. For example, at a duty cycle of 10%, a peak pulsed current density of 40 A/dm^2 is required for an average current density of 4 A/dm^2. In practical applications this would seldom be viable due to limitations of rectifier capacity. As duty cycle is increased it begins to approach DC; so a compromise situation needs to be achieved. If sufficient spare rectifier capacity is available a duty cycle of 33 to 50% is probably the minimum practical value. For applications using high current, such as chromium plating, a value of 50 to 75% would be the lowest usable duty cycle.

After considering the practical limitations of duty cycle it is necessary to consider the effects of frequency, which is defined as the reciprocal of the cycle time, t:

$$f = 1/(t_c + t_p) = 1/t \qquad (6)$$

At high f, the double layer does not have time to charge fully during the t_c or fully discharge during the t_p time. This has a smoothing effect on the applied waveform, which begins to approach DC current, and this limits the maximum useful frequency to around 500 Hz for most applications; however, higher frequencies can be used where very high pulse current densities are employed because the double layer charge and discharge times become shorter as peak pulse current density is increased.

Some manufacturers of pulse-plating equipment advocate the use of very high frequencies, but the practical maximum frequency that can be applied to a plating electrolyte is limited by the capacitance of the double layer at the interface between the plating electrolyte and the article being plated.

THE EFFECT OF PULSED CURRENT ON THE MAXIMUM RATE OF DEPOSITION

Unsubstantiated claims have often been made that pulse plating can improve the maximum rate of deposition obtainable from plating baths by several orders of magnitude. The theory behind this reasoning is that as frequency is increased, the diffusion layer becomes thinner; however, the diffusion layer, which is encountered with pulse plating, also pulses at the high frequency applied to a plating system. The diffusion layer does not have time to disperse completely between pulses, and the total thickness of the diffusion layer approaches that obtained when plating with DC current. Consequently, the use of pulse current has very little effect on the limiting current density. Metal ions cannot be discharged faster than they are supplied to the cathode surface. The rate of supply of metal ions depends only on hydrodynamic and concentration factors and is little influenced by the applied waveform.

The major factors governing the supply of metal ions to the cathode surface are hydrodynamic factors: rate of agitation, viscosity, diffusion coefficient, and the metal ion concentration. The rate of consumption of metal ions depends only on the average current density and is not influenced to any extent by the shape of the applied waveform. Although pulse plating cannot increase the theoretical limiting current density of a plating electrolyte it must be taken into account that the maximum practical current density at which a plating electrolyte is usually operated is only 20 to 30% of the theoretical limiting current density. This is because mass transport effects can produce burning at higher current densities areas. Obviously, there is room for improvement, and higher practical plating rates can sometimes be achieved with pulse current due to improved deposit properties. This effect is attributed to the influence of pulsed current on the electrocrystallization rather than on an enhancement of the rate of mass transport.

THE EFFECT OF PULSE CURRENT ON CURRENT DISTRIBUTION

The cell geometry dictates primary current density distribution; therefore, it is not affected by electrochemical parameters and would be unaffected by the applied current waveform. The primary current distribution is modified in plating solutions by the secondary current distribution, which arises due to the effects of activation (chemical) overpotential. In general the greater the rate of change of potential with increasing current density the more the overall current density distribution tends toward a secondary distribution and, excluding mass transport effects, produces a more even metal distribution. As current density is increased the electrode resistance decreases and the rate of change of potential with current density also becomes less. Thus, as current density is increased the current distribution tends toward a primary distribution and the throwing power usually deteriorates. In electrolytes where metal ions are not strongly complexed and cathodic efficiency is high a low current density usually produces a better throwing power than a high current density. With any form of modulated current, whatever the shape of the waveform and whether unipolar or bipolar pulses are used in order to maintain the same rate of deposition as for DC current, the cathodic current density during the cathodic pulse must be higher than the equivalent DC current density. This means that the overall current density distribution tends toward a primary distribution when pulse or PRC plating are employed. Consequently, the deposit distribution in general would be expected to be less uniform using pulsed current than with direct current; however, in electrolytes where the cathodic efficiency is less than 100%, the use of pulsed current may change the relative efficiencies of metal deposition and hydrogen evolution and may under a particular set of conditions produce an increase in throwing power.

PRACTICAL APPLICATIONS OF PULSE PLATING

The application of pulse current leads to the improvement in the quality of a number of industrial electrodeposits. By using pulse current in comparison with the deposits obtained by DC one can achieve smoother deposits of copper, nickel, and zinc from sulfate solution and gold and copper from cyanide solutions, with the average current densities and plating times being kept equal. Also, an equal or better quality of the deposits of copper, gold, and zinc is obtained at higher current densities under pulse current than under DC conditions. A decrease of grain size of the pulse-plated deposits is generally found to lead to an increased coverage of the substrate with the same quality of the deposited metal, resulting in decreased porosity and surface resistance, and increased density of the metals. It can be expected that this increase in compactness is associated with a decrease in internal stresses and increased ductility and change of hardness of metal deposits.

In situations where hydrogen is codeposited (current efficiency less than 100%) the current distribution can be better in pulse current regimes as compared with DC current.

PULSE-REVERSE PLATING

PRC plating is the bipolar electrodeposition process where DC current is continuously changing its direction (polarity). Quite popular in the 1950s, it then found its major use in improving leveling action in hot cyanide copper plating baths; however, the use of these baths was drastically reduced due to environmental problems and inherent build-up of carbonates, and PRC was relegated to secondary duties such as for very effective electrocleaning, as well as for derusting and desmutting. Theoretical studies were, therefore, not pursued to any extent.

In the 1970s new theoretical contributions were introduced, and in the 1980s and 1990s it became quite obvious that PRC can give answers to many complicated electrodeposition problems. Theory became much more complex and intriguing. The essence of current reversal is that during metal electrodeposition the polarity automatically changes and the duration of the reverse (anodic) current is normally a small fraction, e.g., 20% or less, of the duration of the current in the direct (cathodic) direction.

The bottom part of Fig. 1 shows the different kinds of nonstationary PRC currents. Periodically reversed current is characterized by the following properties: a current in the forward direction (cathodic polarization current), i_c; a time for the metal deposition (cathode period), t_c; anodic polarization (reverse) time period, t_a; and a total period of the current reversal, $t_a + t_c$. The average density is given by equation 4.

In the electrodeposition of metals by a reversed current the electricity q_c flowing through the electrodes during the cathode period, t_c, must be greater than the amount of electricity q_a flowing during the time of the anode period t_a, i.e., $i_c\, t_c > i_a\, t_a$. Consequently, by this method of deposition, the whole quantity of electricity is not consumed in the formation of the deposit. A significantly smaller portion is expended for the anodic polarization (often called deplating, stripping, or reversing) of the plated products. During each total period of plating with current reversal a layer of metal of a determined thickness is built up on the surface of the products, and during anodic polarization (t_a), part of the deposited layer is dissolved.

In general, to increase the rate of metal deposition, conditions at the electrode surface must be created under which the limiting cathodic current density and passivating anodic current are significantly increased. At the same time a high metal-to-current efficiency must be maintained and the protective properties of the electrodeposits must satisfy the requirements. As was noted earlier, until relatively recently, these conditions were met mainly by changing DC variables: the metal concentration, temperature and agitation of the bath, as well as by introducing various additives.

Despite the fact that PRC deposition occurs with the incomplete use of the whole quantity of electricity applied on the electrodes, this method of metal deposition often permits acceleration of the electroplating rates. Faster deposition can be accomplished by using a higher working current densities than compared with a DC current. Initially, this is caused by the prevention of depletion of metal ions in the cathode double layer, to which the anodic dissolution of the deposit contributes. The upper limit of the working current densities during the metal deposition is a function of the parameters of the reversed current t_a and i_a and also of the length of the total period. The limiting cathodic current density usually increases with an increase of the ratio t_a/t_c and with a decrease in total time.

The a higher working current density during the PRC deposition as compared with DC plating is a result of the periodic depolarization of the electrodes. Such an effect of the current reversal on the electrode processes, as well as the electropolishing action of the anodic current on the deposit, permits ensuing electrocrystallization on the cathode surface in the preferred direction (smaller crystal grains) under a higher working (practical) current density. During the cathodic period this leads to grain refinement usually associated with unipolar, pulse current pulse plating, which is now further supported by the disturbance of growth steps by the periodic inversion of the current.

In a number of DC electroplating processes for example, during the electrodeposition of certain metals from solutions of their simple salts, the upper limit of the working current density can be, under certain conditions, held close in magnitude to the theoretical limiting current. Often, however, under real, actual plating conditions, the working current density of the cathode is limited to the admissible upper limit of the anodic current density. Exceeding this limit can cause anode passivation when the electroplating bath is operating in a DC mode (e.g., nickel, brass, and cyanide and acid copper baths). Now, current reversal can prevent passivation of the anodes during the period of high cathodic current and sometimes contributes to a significant increase of the upper limit of the anode working current density and, thus, in turn, increases the maximum working cathode current density.

PRACTICAL APPLICATIONS OF PULSE-REVERSE PLATING

Electrolytes containing organic additives may undergo changes in the deposition mechanism when PRC current is used, which can produce changes in the uniformity of the deposition that have a beneficial affect on throwing power. When electrodepositing a copper from acid baths containing organic additives substantial improvements in hole throwing power can be achieved for deposition of copper on printed circuit boards.

The use of a current of alternating polarity permits not only increasing the working current density, but as a result of the periodic action of the anodic current on the deposited layer of metal, the deposit acquires better protective properties as demonstrated in actual practice for acid copper, nickel, gold, chromium, and zinc. For a number of processes, current reversal is the means of achieving smoother and brighter deposits, better current distribution, and less porous deposits with lower internal stresses. In the case of chromium plating higher current efficiency is easily achieved, whereas for nickel plating, brightness and leveling can be obtained with much reduced concentration of organic additives with additional important benefits of increased ductility and reduced stress.

It is obvious that PRC plating has more variables than DC plating. More variables mean more complex plating equipment and controls but also wider choice of deposit characteristics that can be tailored for a particular application, e.g., increased corrosion protection, leveling, different hardness, ductility, stress values, and alloy composition and, in the case of chromium, results in higher cathode current efficiency.

METALLIZING NONCONDUCTORS

by Charles Davidoff

Consultant, Port Washington, N.Y.

There are many parts whose functions are more adequately served when the properties of both a metal and nonmetal (plastic or ceramic) are combined.

In these instances, the part is generally manufactured of the nonconductor and the metal added to its significant surfaces to impart specific metallic properties. Typical examples of this are:

1. For strength, as in the plating of a thick copper envelope around a woman's high heel for added flexural strength and prevention of splitting from nails when being repaired with new lifts.
2. For electrical conductivity, as in the printed circuit, where a patterned copper film on a nonconductor, such as plastic or ceramic, serves as the wiring in an electronic circuit.
3. For metallic appearance, as in the metallizing of buttons, drawer pulls, door knobs, automotive and appliance hardware, toys, etc., made of plastic. Among the nonconductive materials, which have been successfully metallized are aluminum oxide, beryllium oxide, glass, wood, wax, rubber, silicone, phenolic, urea, melamine, glass laminate, polyacetate, polystyrene, polycarbonate, epoxy, polyethylene, polypropylene, acrylic, fluorocarbon, polysulfone, polyphenylene, nylon, acrylonitrile-butadiene-styrene (ABS), polyvinyl chloride, polyimide, and others.

DESIGN CRITERIA

To metallize a plastic part, the following design criteria must be considered.

1. The wall thickness, where the plating rack spring is to make contact, should be thick enough to withstand contact pressure. Generally, ⅛ in. is considered good.
2. Use generous radii at corners and angles. An internal radius should be greater than an external. Try to keep 1⁄16 in. as a minimum.
3. Holes should be through the part wherever possible to minimize entrapment of treatment fluids. Avoid blind holes.
4. Avoid surface defects, which identify sink marks, ejection marks, blisters, parting lines, gate marks, flash, and weld lines.
5. Reinforcing ribs should be no more than one-half as thick as the adjoining wall and not taller than one and a half times the adjoining wall.
6. Bosses and studs should be limited in height to no more than twice their thickness.
7. *Caution!* Plastic parts, assembled by welding, cementing, or with mechanical fasteners are not candidates for metallizing.

DEVELOPING GOOD ADHESION

The properties required of the nonconductor for good adhesion of a metallized film are a mechanically roughened surface, an etched surface, or a surface that can be made hydrophilic.

Roughening is most easily applied to small parts. This is done by tumbling in a slurry of pumice and water at 40 to 50 rpm for 1 to 4 hours.

Etching is done with strong acids, i.e., for:

ABS (acrylonitrile-butadiene-styrene): A mixture of chromic acid (6 to 7 oz/gal) and sulfuric acid with a weight ratio of CrO_3/H_2SO_4 of 0.4:1 to 0.6:1. The bath is maintained at 135°F and the time of immersion is 10 to 15 minutes. This must be followed by rinsing and neutralization in sodium metabisulfite (2 oz/gal) at 120°F. The CrO_3/H_2SO_4 etch has a limited life of approximately 300 ft^2/gal.

Polyimides: Dip in 10 to 38% of nitric acid, followed by neutralization (U.S. Patent 4,959,121).

Polysulfone: The process starts with a 5 to 70% aqueous dip in dichloropropanol, dichloroacetic acid, or trichloroacetic acid for 0.5 to 10 min at 135 to 145°F. After rinsing it is followed with the chromic sulfuric acid etch (U.S. Patent 4,125,649).

Polycarbonates and polyesters: Use the same process as for polysulfones.

Fluorocarbons: Fluorocarbon resins require special initial preparation, which is unlike preparation for other resins. This procedure conditions the resin in a solution composed of anhydrous ammonia and an alkali metal, such as sodium, or in a complex prepared by mixing the metal sodium with naphthalene in the solvent tetrahydrofuran. The latter method is considered more practical. The solution is made by first mixing 1 mol or 120 g of naphthalene in 1 L of tetrahydrofuran and then adding 1 mol or 23 g of sodium metal (cut into small pieces). This is stirred together for 2 hours at room temperature. Air should be excluded as much as possible during preparation, use, and storage. This is a very hazardous mixture. This mixture deteriorates with time; therefore, make sure it is still effective if it has been stored. Following this conditioning, the resin is treated like all other resins, following the normal steps of sensitizing, nucleating, and then applying a conductive metal film prior to electroplating.

These pretreatments help to develop the maximum adhesion of metal to plastic.

SENSITIZE, NUCLEATE, AND ACCELERATE

The next step is to sensitize the surface to accept the initial metal film. This is a brief soak in a stannous chloride solution or similar formula with the same function.

There are many formulas indicated. The usual ones contain stannous chloride and hydrochloric acid in varying proportions. The tolerance for ratio variations is wide. Two typical formulas are as follows:

1. Stannous chloride, 10 g
   Hydrochloric acid, 40 ml
   Water, 1 L
2. Stannous chloride, 180 g
   Hydrochloric acid, 180 ml
   Water, 200 ml

It has also been found that blending a small amount of aged stannous chloride sensitizer with a new batch will often help to make unplatable plastic platable. Adding sodium chloride to the sensitizer will improve its performance, i.e., stannous chloride, 22 g/L; hydrochloric acid, 20 g/L; and sodium chloride, 150 g/L.

Other sensitizers have been used such as gold chloride, palladium chloride, platinum chloride, stannous fluoborate, silicon tetrachloride, and titanium tetrachloride. A recent patent suggests the use of alkali gold sulfite.

Sometimes gold chloride, platinum chloride, or palladium chloride is used as an additional or second sensitizing step. When one is so used we often refer to the treatment as nucleation. A typical palladium chloride bath for this function is:

Palladium chloride, 0.005 to 2 g/L
Hydrochloric acid, 0.1 to 2 g/L

When stannous chloride is followed by palladium chloride, stannous chloride ions Sn^{2+} are absorbed on the surface. When then dipped in the palladium chloride, a redox reaction takes place, precipitating the catalytic metal palladium on the surface.

$$Sn^{2+} + Pd^{2+} \rightarrow Sn^{4+} + Pd^0$$

There are mixed sensitizers of stannous chloride and palladium chloride, i.e.,

Palladium chloride, 1 g
Hydrochloric acid (37%), 300 ml
Stannous chloride, 50 g
Water, 600 ml
(U.S. Patent application, Serial 712,575; also see U.S. Patent 3,650,913)

This step is often followed by an accelerator dip, which consists of ammonium bifluoride, 120 g/L.

FILMS PRECIPITATED ON CATALYTIC SURFACES

These films serve as a basis for initial conductive support and consist of copper, nickel, or silver. Typical formation of such films is as follows:

Copper

A copper film may be deposited by reduction with formaldehyde from a Fehling solution to which a small amount of silver is added. A typical example is:

Anhydrous copper sulfate, 2 g
Silver nitrate, 0.2 g
Rochelle salt, 4 g
Potassium hydroxide, 4 g
Distilled water, 100 ml
(Reduce with 5% formaldehyde solution)

Another copper formula, reported by E.B. Saubestre, is as follows:

Solution A:

Rochelle salt, 170 g/L
Sodium hydroxide, 50 g/L
Copper sulfate, 35 g/L
Sodium carbonate, 30 g/L
Versene-T, 20 g/L

Solution B:

Formaldehyde, 37% by weight

It is suggested that, immediately prior to use, 5 volumes of solution A be mixed with 1 volume of solution B . The solution should be used at room temperature.

Another useful formula reported by the same author is:

Copper sulfate (pentahydrate), 5 g/L

Sodium hydroxide, 7 g/L
Formaldehyde (37% w/v), 10 ml/L
Rochelle salts, 25 g/L

This is considered a rather stable solution provided it is kept free of particles such as dust. These particles tend to serve as points of premature nucleation, which cause the copper to precipitate out of solution.

The copper film precipitation can be initiated by dipping in a 10% sodium hydroxide solution just prior to immersing in the copper bath.

Many other copper film formulas are in the literature.

Nickel

Another method of applying a metal film on nonconductors is by catalytic deposition of nickel, sometimes referred to as "electroless nickel." This works well with thermoset-type plastics. Thermoplastics with high softening points can be also be coated, but only with caution and care because of the temperature instability characteristic of this group of plastics.

A.S.T.M. publication No. 265 suggests the following preparatory procedure:

a. Clean
b. Roughen
c. Sensitize in stannous chloride at 80°F (70 g/L stannous chloride and 40 g/L hydrochloric acid)
d. Rinse
e. Immerse in cold palladium chloride solution (1 g/L), containing 1 ml of concentrated hydrochloric acid.
f. Rinse
g. Immerse at 200°F in the following solution:
  Nickel chloride, 30 g
  Sodium hydrophospite, 10 g
  Sodium citrate, 10 g
  Water, 1,000 g
  pH, 4–6
  Plating rate, 0.2 mil/hr

Another typical cycle is:

a. Alkaline soak—1 min at 65°C
b. Rinse
c. Etch—5 min at room temperature
e. Rinse
f. Immerse in sensitizer—5 min at room temperature
g. Rinse
h. Immerse in nucleator—1 min at room temperature
i. Rinse
j. Immerse in ammonium bifluoride accelerator—2 min at 40°C
k. Rinse
l. Immerse in electroless nickel at 70°C

The alkaline soak is to clean the surface. The etch is to modify the resin surface to obtain better adhesion of the plated film. The sensitizer and the catalyst or nucleator provide tin-palladium sites for metal precipitation. The accelerator removes the complex tin species and, thereby, activates the catalyst sites. The electroless deposit provides the conductive film to which further plating may proceed.

The literature now shows many adaptations of the hydrophosphite reduction procedure, which may be applied to cobalt, nickel-cobalt alloys, iron-nickel alloys, etc. The subject of catalytic plating is covered elsewhere in this *Guidebook* book under the title Electroless Plating.

Silver

Silver films are excellent starting surfaces for metallizing nonconductors.

A good silver film is the type deposited by the Brashear Formula. It consists of two parts of a silver fulminate solution and a reducing solution. When these two are combined, a silver film results.

Silver Fulminate Solution:

Silver nitrate, 20 g
Potassium hydroxide, 10 g
Distilled water, 400 ml

A precipitate is formed and is just dissolved with ammonium hydroxide (~50 ml).

Caution: To avoid formation of explosive fulminates, the silver salt, caustic, and ammonia should *never* be mixed in concentrated form, but should be diluted with water first. Containers that have held this fulminate solution should be washed carefully and never allowed to dry with any residual material. Dry, this material is explosive.

Reducing Solution:

Cane sugar, 90 g
Nitric acid, 4 ml
Distilled water, 1 L
Boil and cool before using

Immediately before using, mix one part of reducer with four parts of silver. A reaction temperature of 68°F is preferable.

METALLIZING NATURAL POROUS PRODUCTS

Natural products, such as wood and leather, or products, such as plaster and sea shells, must be presealed. Without presealing, there could be chemical reaction between the item being coated and the process chemicals. Also, presealing prevents absorption of process chemicals, which would gradually bleed and mar the finished surface. Presealing can be done with various lacquers, acrylics, ½ second butyrate, etc.

The use of conductive paints to serve as the basis for metallizing natural products is the preferred method. The conductive ingredient is a metal powder such as silver flake, copper flake, or gold flake.

Silver paint containing 60 to 70% silver flake is preferred for brushing and lesser quantities for spraying. Cellulose esters and methacrylate-type resins are used as binders. Epoxy-based paints are also available. These paints are sold by many manufacturers under the descriptive name of "Silver Conductive Paint."

A copper paint, sometimes called bronzing paint, is often used for applications as a conducting film. The mixture consists of the following:

Nitrocellulose lacquer, 1 fl oz
Lacquer thinner, 7 fl oz

Copper lining powder, 2 oz

Only enough for immediate use should be prepared, as the metal powder often causes the lacquer to jell. If the copper powder is greasy, it should be washed with thinner before using. If sprayed, the copper paint should be applied with the gun held at a distance so that the film dries almost as soon as it reaches the surface. A glossy appearance indicates that the copper is coated with a layer of lacquer, which will prevent passage of current. The goal is to spray the coating so that a minimum of lacquer remains on the surface of the copper powder.

A good method of ensuring that the surface is conductive is to dip the coated article in a solution of about 1 oz/gal silver cyanide and 4 oz/gal sodium cyanide. Absence of an immersion silver deposit in areas will indicate that the lacquer film has not been applied correctly.

METALLIZING BY FIRING

Design patterns of silver, gold, or platinum on glass or ceramic may be done by firing fine powders or compounds that are reducible with heat in a base with flux and oil.

Typical formulas for silver, gold, and platinum follow.

Silver

Silver powder, 60 g
Lead borate, 3 g
Bismuth nitrate, 1.5 g
Lead fluoborate, 5.5 g
Lavender oil, 30 g

The powders are suspended to a paint consistency with the lavender oil. Dry and fire at 1,200°F.

Gold

Gold (very fine powder), 10 g
Bismuth nitrate, 0.92 g
Sodium borate, 0.08 g
Lavender oil, ~10 g

Suspend the powders to a paint consistency with the lavender oil. Apply, dry, and fire at 1,100°F.

Platinum

Platinum chloride, 5 g
Lead oxide, 0.1 g
Lead borate, 0.1 g
Lavender oil, 10 g

Suspend the powders in the lavender oil to a paint consistency. Apply, dry, and fire at 1,200°F.

Both the gold and platinum films may alternatively be prepared by mixing the dry chloride salts with a small amount of rosemary oil and diluting to a thick paste. This can be further diluted with lavender oil for ease of application.

SPRAY COATING

In some applications, the production of a heavy metal film is not required; the original properties of the plastic are perfectly adequate for the application. The only purpose of the metal spray coat is to produce a mirror film that gives the product the appearance of being made of metal. There is a special surface lacquering before and after the application of the mirror film.

For the most part, this type of film is produced by spraying. The sensitizing is done with a single nozzle gun spraying sensitizer (stannous chloride solution), water washing, then spraying to develop the silver film using a double nozzle spray gun. This is a unique gun that proportions out a spray of silver fulminate from one nozzle and a spray of reducing agent from the other. These sprays are made to meet and mix at a point about 6 to 8 in. from the nozzle heads. The work to be coated is kept in the mixing plane until a satisfactory mirror forms. This usually takes a few seconds. The solutions used are most often proprietary mixes consisting of a silver fulminate solution made by just redissolving the silver precipitate that first forms by the addition of ammonia (approximately 10 g of silver nitrate and 10 ml of ammonium hydroxide per liter of water), and a reducer made of hydrazine salt with some alkali.

A typical spray silvering solution and reducer consists of the following:

Silver Solution:

Silver nitrate, 2.5 oz/gal
Ammonia, 60 ml/gal approx.

Reducer Solution:

37% formaldehyde, 270 cc/gal
Triethanolamine, 25 cc/gal

A spray formula reported for gold is as follows:

Gold Solution:

Gold chloride, 25 g/L
Sodium carbonate, 25 g/L

This formula works better if the gold chloride/sodium carbonate solution is allowed to age for 24 hr before using.

Reducer Solution:

Formaldehyde, 40 g/L
Sodium carbonate, 40 g/L

All spraying should be done in stainless steel spray booths. They should be washed down frequently.

ELECTROFORMING

by Tony Hart and Alec Watson

The Nickel Development Institute, Toronto

Electroforming can be defined as a process that employs technology similar to that used for electroplating but which is used for manufacturing metallic articles, rather than as a means of producing surface coatings.

The principles of the electroforming process are demonstrated in Fig. 1. This shows a suitable metal, such as nickel, being electrodeposited onto the surface of a conical mandrel (the term mandrel is used to describe the former onto which an electroform is grown). When the deposit has attained a sufficient thickness it is then separated from the mandrel to become a metallic product with a totally independent existence.

The importance of electroforming in the modern world and the degree to which it impinges on everyday life often is not appreciated, even by professional engineers and technologists. This contribution, therefore, sets out to describe the nature of the electroforming process and its associated industry and to provide basic information regarding production techniques, together with an outline of important commercial applications.

THE SIZE OF THE ELECTROFORMING INDUSTRY

Electroforming is not a new technology; it has existed as long as electroplating, the first applications being recorded around 1840. With hindsight, however, it does seem to be a

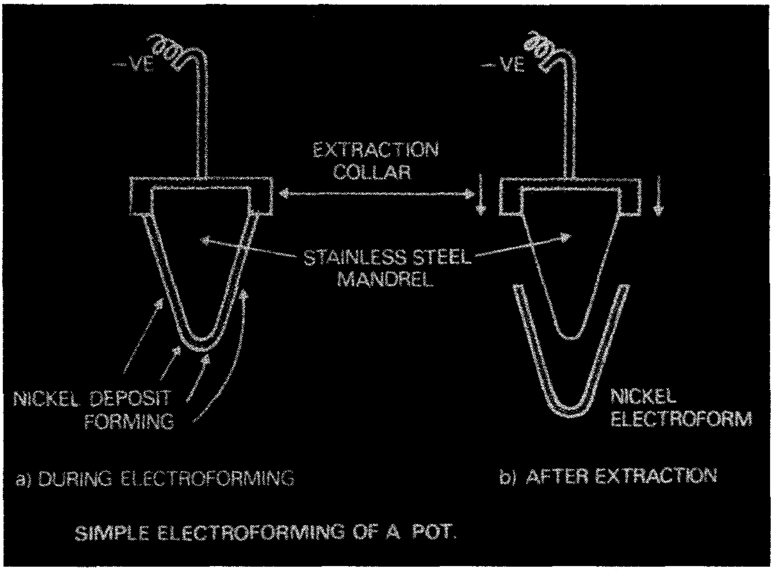


Fig. 1. Schematic diagram showing production of simple nickel electroform.

process that was well ahead of its time. Little use was made of it during the 19th century, and only limited applications appeared in the first half of the 20th.

The process really has come in to its own during the last 40–50 years. This has been due to the inherent advantages of electroforming that enabled engineers, designers, and technologists to solve the problems of manufacturing specific products required by a very wide range of applications and industries, including many high-technology ones.

One very important aspect of the electroforming industry that is not widely appreciated is its size. The worldwide turnover during the mid-199Os has been estimated at $2 billion per year. This figure was derived from calculations based on the quantities of the two major metals used by this industry—80,000 metric tons/year of copper and 5,000 metric tons/year of nickel. The value of the primary metal used in each application was multiplied by a factor—supplied by companies in the particular market sector—relating selling price of the electroformed article to basic metal cost. Using those factors, together with normal geographical considerations, the worldwide size of the electroforming industry was calculated, yielding the figures just discussed.

In addition to this very significant size the electroforming industry has also shown a consistent pattern of growth over a long period of time. This has been due to requirements from new technologies increasing at a greater rate than the decline of outdated applications. Frequently, this has resulted in steady growth of the industry even in times of general recession.

WHY AND WHERE ELECTROFORMING IS USED

Electroforming cannot always be regarded as the most economical method of manufacturing metallic products. If it is possible to use conventional metal working techniques, such as pressing or forging, these generally will be employed on cost grounds.

There is, however, a very wide range of situations in which electroforming is the preferred method of manufacture and many other instances where it is the only one that can be used to produce a particular product. Applications where it is employed successfully always depend on the exploitation of one or more of the advantages of the electroforming process, the principal ones being as follows.

Accuracy of Reproduction

Electroforming is by far the most accurate method of manufacturing metallic articles. Both the dimensional tolerances that can be achieved and the ability of the process to reproduce surface detail with absolute fidelity are unmatched by any other metal-fabrication processes.

An excellent example demonstrating this critical advantage of the technology is a very familiar one in the modern world—the manufacture of molds for compact disk (CD) production. Information is stored on a CD in the form of a continuous helical track consisting of shallow depressions. These are typically 0.1-micrometer deep and 0.2-micrometer wide, and they vary in length from 0.2 to 2.0 micrometers, with an intertrack spacing of 1.6 micrometers. There are frequently 3×10^{10} such depressions on a CD, all of which must be of the correct size and shape and in the correct position to achieve the required performance. Electroforming is the only technique that is sufficiently accurate to be used to produce molds for CD manufacture.

This key advantage of electroforming is why the process is used to produce many other types of molds, dies, and other products requiring very high-dimensional accuracy such as wave guides. It also enables electroforming to be used to reproduce natural finishes, such as wood grain and leather, with total realism.

Manufacture of Thin-Section Products

It is, perhaps, logical that electroforming, which produces a metallic article by building up the structure of the material atom layer by atom layer, should be an excellent method for manufacturing thin-walled products. In conventional metal working processes the metal is normally cast as a massive billet or ingot, which needs to be progressively reduced in size to yield a thin-section final product. This involves multiple working processes and can, therefore, be very costly as well as inefficient in terms of energy consumption.

The production of foil and mesh products is by far the biggest industrial use of electroforming. With copper the most important product is plain unperforated foil whereas for nickel perforated mesh products, in particular screen-printing cylinders, predominate. Further details of a number of commercially important thin-walled products are given later in the section that describes applications.

Manufacture of Complex Shapes

An increasingly wide range of metallic products required by modern technology is of an extremely complex shape. Many of these are manufactured by electroforming because it is by far the most economical method of production. In a large number of cases, the technique is the only method available for producing the shape required. A good example of this is the waveguides used extensively in radar and microwave technology. There are many other instances of aerospace and defense uses, some of which are discussed in the applications section.

Manufacture of Large Products or Molds

For the manufacture of very large products and molds, particularly ones with thin walls, electroforming can be the most economical method of production. It avoids the very high cost and difficulty of fabricating and machining large objects and, at the same time, minimizes raw material usage.

Manufacture of Very Small Products or Molds

In recent years, a radical new development of electroforming technology called the LIGA process has appeared. This enables extremely small components, sometimes with dimensions of only a fraction of millimeter, to be made with very high precision. This process is becoming established in a number of industries.

HOW ELECTROFORMING IS DONE

Differences Between Electroforming and Electroplating

Although the basic technology of electroforming is very closely related to that used for electroplating, there are a number of important differences.

Deposit Thickness

Electroplated deposits used as coatings—in order to confer corrosion resistance, wear resistance, or simply aesthetic appeal—are generally 1- to 30-micrometers thick. Electroformed products, however, need sufficient mechanical strength to be able to exist independently of the mandrel onto which they are deposited. They are, therefore, normally much thicker, ranging from foils of 10-micron thickness to mold faces that can be up to 5-millimeters thick. Electroformed backings for molds have been produced as thick as 50 millimeters.

Substrate Adhesion

If an electroplated coating is to fulfill its function it is essential that the adhesion between the deposit and the substrate be good. Electroforming, however, requires exactly the opposite.

Table I. Metals and Alloys Used in Electroforming

Metals	*Alloys*
Nickel	Nickel-cobalt
Copper	
Iron	
Silver	
Gold	Gold alloys
Aluminum	

It is vital that there is little or no adhesion between the deposit and the mandrel so that the product can be separated without damage when the forming process is complete. Whereas in electroplating the pretreatment processes are selected to maximize deposit adhesion, electroforming pretreatments are specifically chosen to reduce the adhesion between the deposit and the mandrel to the minimum required to prevent premature separation.

Internal Stress in the Electrodeposit

Because electroforming requires that the adhesion between mandrel and electrodeposit should be minimal, it is vital that the internal stress in the deposit is controlled. Normally, this means maintaining it as low as possible.

Stresses are usually present in electrodeposited metals and may be either tensile or compressive in nature. Both tensile and compressive internal stresses, if sufficiently high, can produce distortion of the deposit if it is not restrained by the substrate. In electroforming, where there is no such restraint, it is, therefore, essential to select deposition processes that give low internal stresses in order to avoid unacceptable dimensional changes or gross distortion of the product. It is for this reason that sulfamate-based solutions, rather than those employing the cheaper sulfate salt, often are preferred for nickel electroforming.

Metals and Associated Processes Used for Electroforming

The metals and alloys that can be used in electroforming are shown in Table I.

The choice of materials is limited not only by the normal constraints that apply to electrodeposition in general but also by the additional requirement for low internal deposit stress. Thus, a metal such as chromium, which would have many desirable properties as an electroform, particularly in relation to its hardness, cannot be used because of the extremely high internal tensile stresses generated in the electrodeposited metal.

Nickel

Nickel can be considered the workhorse of the electroforming industry. Although a larger tonnage of copper than nickel is deposited, it is only used for a very limited range of products. It is probable that 95% or more of the products manufactured by electroforming are produced in nickel. This is due to a favorable combination of properties, both of the electrodeposit and of the deposition processes.

Electroformed nickel shows excellent strength, toughness, and ductility and is extremely resistant to corrosion in a wide range of environments. In addition it can readily be deposited in a low-stress condition, and its hardness and strength can be varied over a wide range by selecting appropriate deposition conditions. There are a number of deposition processes available that are suitable for electroforming of nickel. They are generally highly reliable and relatively easy to control, being both chemically and electrochemically stable and environmentally friendly. The operating parameters for these processes are also well documented, which allows a substantial amount of control to be exercised over the properties of the deposits obtained.

Table II. The Conventional Nickel Sulfamate Solution

$Ni(NH_2SO_3)_2 \cdot 4H_2O$	350–450 g/L
$NiCl_2 \cdot 7H_2O$	5–30 g/L
H_3BO_3	35–40 g/L

There is a strong preference for nickel sulfamate-based solutions in the electroforming industry. The deposits that they produce not only have a low internal stress, which is essential for this application, but the electrolytes are stable, reliable, and simple to operate. Conventional nickel sulfamate solution has an uncomplicated makeup. A typical composition range is given in Table II.

In most published formulations chloride is included. This has been conventional wisdom for many years and is based on the fact that this anion is required for good dissolution of nonactivated nickel anodes; however, if one of the sulfur-activated grades of nickel anode materials, which are readily available commercially, is used, then a chloride-free solution will operate without problem at normal anode current densities. This is a considerable advantage because the chloride ion increases tensile stress in the deposit so that operating a chloride-free solution approaches closer to the ideal stress-free condition.

Nickel sulfamate solutions can be used for long periods of time with minimal chemical analysis. There is a slow, steady rise in the solution pH due to a small imbalance between the cathodic and anodic current efficiencies, but this can easily be controlled by sulfamic acid additions. The same imbalance, however, also results in a gradual rise in nickel salt concentration in situations where drag-out is low, which is frequently the case in electroforming. This may require periodic dilution of the solution to maintain the optimum concentration.

Nickel sulfamate-based solutions can also be used with a number of organic addition agents. These provide a much wider range of deposit properties than can be achieved with standard processes without additives. For example additive-free solutions will give deposits with hardnesses around 200 HV. This can be increased to 500–600 HV by the use of suitable additives.

Nickel sulfate-based solutions are also used for electroforming but always require the presence of an addition agent, such as the sodium salt of saccharin, to reduce the internal tensile stress to a tolerable level. These solutions are generally based on the conventional Watts-type composition given in Table III.

These basis solutions are also extremely stable, requiring only additions of acid to counteract the natural pH rise; however, the organic additives generally require frequent and more sophisticated analysis in order to maintain the required properties in the deposit. They are, thus, less suitable than the conventional sulfamate process for use in situations where regular chemical analysis is not available.

Nickel fluoborate solutions are also mentioned in the literature, but there are few commercial applications.

One further advantage related to both sulfamate- and sulfate-based nickel electroforming processes is that there is a considerable body of information available in the literature regarding the use of additives, both organic and inorganic, to these solutions.

Table III. Watts-Type Nickel Solution

$NiSO_4 \cdot 6H_2O$	250–400 g/L
$NiCl_2 \cdot 7H_2O$	25–60 g/L
H_3BO_3	30–40 g/L

Table IV. Acid Copper Solution

$CuSO_4 \cdot 5H_2O$	70–250 g/L
H_2SO_4	50–200 g/L

Copper

In the region of 80,000 metric tons of copper is used for electroforming each year. The vast majority of this is, however, for one single application—the production of thin foil used for the construction of printed circuit boards. Other uses of copper are mostly limited to those where electrical conductivity is also the property of prime importance, for example waveguides and spark erosion electrodes. There are also a few miscellaneous uses, such as backing of nickel mold faces, production of loudspeaker cones, and parts for musical instruments.

Copper, although cheaper than nickel, is not used for the majority of electroforming applications because its mechanical properties are not as good as those of nickel, and it has less resistance to corrosion in many environments. In addition, the processes for depositing copper are, overall, not so attractive for general purpose electroforming.

The solution most commonly used for copper electroforming is the simple acid copper sulfate. This can operate over a wide composition range, as shown in Table IV.

This solution is stable and simple to operate and produces deposits with very low stress levels; however, owing to its very high sulfuric acid concentration, this formulation is very corrosive both to equipment and its surrounding environment.

Acid copper sulfate solutions are used for the production of electroformed copper foil using an inert anode system and chemical dissolution of scrap copper to maintain the solution balance. This enables the gap between cathode and anode to be small and accurately controlled, thus minimizing power consumption.

Acid copper solutions are also used with organic additives developed for decorative bright acid copper plating. In contrast to additives for nickel processes, however, there is relatively little information available on the effects that these materials have on deposit stress or hardness.

Copper cyanide solutions can also be used for electroforming, but the internal deposit stress is considerably greater than that produced by acid sulfate solutions. This, combined with the toxicity and effluent problems associated with cyanide solutions plus the relatively complex control required of the solution chemistry, has limited its applications. Cyanide processes have, however, been used with periodic current reversal. This produces very uniform metal distribution and is used for thick deposits for backing electroformed nickel mold faces.

The use of copper fluoborate solutions for electroforming appears to be very limited, although they are mentioned in the literature. The deposit properties, however, appear to offer few advantages over those from acid copper formulations.

The use of copper pyrophosphate solutions seems to be confined to electroforming of spark erosion electrodes.

Iron

Electroforming of iron is technically possible, but despite the low cost of the metal, it has never found any successful commercial application. This is due to its very high susceptibility to corrosion and also to the difficulty in controlling iron deposition processes as a result of the inherent instability of the ferrous ion.

A process was developed some years ago in the United Kingdom for the continuous deposition of iron foil but has never achieved commercial acceptability.

Silver

Silver is employed to a limited extent in applications in which the cost can be justified. These can be functional uses, generally for electronics, in which the high electrical conductivity of silver is important, or for purely decorative ones, such as jewelry.

Only cyanide-based processes have been used successfully for silver electroforming. These produce deposits with good physical properties together with acceptable levels of internal stress. Bright silver can be deposited from proprietary solutions and is used in the jewelry and silverware industry.

Gold

The major use of gold electroforming is for jewelry and other decorative products; however, there are also a number of functional applications of gold electroforms, for example, prostheses for medical purposes and crowns and bridges in dentistry.

Most of the gold electroforming solutions in commercial use are cyanide-based; many proprietary formulations are available.

Aluminum

Aluminum cannot be electrodeposited from aqueous solutions, although nonaqueous processes do exist, but these require the complete exclusion of both oxygen and water from the system. A process has been developed in Germany for electroforming aluminum, but the equipment is very expensive. There have been few successful applications, use being confined to the aerospace industry where the weight saving can justify the expense.

Electroformed Alloys

There is no commercially viable system for copper alloy electroforming, and the only one used commercially for nickel alloys is that for the deposition of binary alloys with cobalt. These can be produced from a sulfamate-based solution, which gives deposits with a hardness in the region of 300–350 HV. This is much harder than pure nickel (200–220 HV) but not as hard as organically hardened nickel deposits (500–600 HV).

Nickel hardened with cobalt has the advantage that it is sulfur free. The organic compounds used as hardening agents for nickel all contain sulfur, and invariably small amounts of this element are codeposited. If the metal is then subsequently heated above approximately 200°C, the sulfur forms nickel sulfide at the grain boundaries of the deposit, giving rise to serious embrittlement. Cobalt-hardened deposits avoid this disadvantage.

The only other alloys used for electroforming are based on gold. These are for jewelry applications where it is essential to control the alloy composition closely so that the products will be acceptable for hallmarking. To maintain tight composition, a special computerized system is necessary, which can be quite expensive to install.

Mandrel Technology

For the successful production of any electroformed product, the design and construction of the mandrel are of utmost importance. An exhaustive coverage of this topic is beyond the scope of this review; so this section must necessarily be confined to a description of the principles.

There are basically two type of mandrels: those that can be removed intact from the electroform, generally referred to as rigid or permanent mandrels, and those that when removed from the electroform are in some way distorted or destroyed, called temporary mandrels. If an electroform is to have reentrant shapes or angles in its geometry, a temporary mandrel must be used. If not, a rigid mandrel can be used.

Rigid Mandrels

A number of materials, both metallic and nonmetallic, are used as rigid mandrels. The material chosen must be capable of being formed into the correct shape and dimensions and, in many cases, needs to be resistant to damage and corrosion. The material must also not contaminate the process solution in which the electroform is deposited.

Suitable metallic materials include stainless steel (preferably an austenitic grade), copper, brass, mild steel, aluminum and its alloys, and electroformed or electrodeposited nickel.

Stainless steel can be used directly as a mandrel material following cleaning and suitable surface treatment. Copper and brass, after suitable surface preparation treatments, can also be used directly; however, they may be electroplated with nickel or nickel plus chromium to give a more corrosion-resistant surface. Mild steel mandrels are almost always treated in this way.

Electroforming of nickel onto nickel mandrels is a widely used technique, enabling sequential replication to be carried out. It is the basis of production for audio records, CDs, and holograms.

Nonmetallic materials used as rigid mandrels include thermoplastic resins, thermosetting plastic resins, waxes, and photosensitive resins.

Photosensitive resins are commercially important mandrel materials that are used to reproduce the highly accurate surface detail necessary in production of CDs and holograms.

Nonrigid Mandrels

There are various types of nonrigid mandrel employing different principles to permit subsequent removal from complex-shaped electroforms with reentrant angles. They include the following:

Fusible materials: Both low melting point alloys, usually bismuth-based, and waxes can be used for mandrels, which are removed by heating above the melting point of the material.

Soluble materials: Aluminum, and to a lesser extent zinc, alloys can readily be dissolved in sodium hydroxide solution. This enables them to be removed from within nickel electroforms because nickel is highly resistant to strong alkaline solutions.

Flexible materials: Readily deformed materials, such as plasticized polyvinylchloride, are used for mandrels that are mechanically collapsed into the electroform to facilitate their removal.

Mandrel Preparation Techniques

Both electrically conductive and insulating materials are used to produce mandrels.

With the conductive ones it is necessary that, following thorough cleaning, the surface be treated so as to ensure that the electroform does not adhere, thus allowing separation. The treatment used depends on the mandrel material. One of the simplest is the use of sodium dichromate solution to give a passive parting film on the surface of stainless steel or nickel.

With insulating mandrel materials, it is necessary to provide an electrically conductive layer on the mandrel surface onto which the electrodeposition process can initiate. This can be done in a number of ways, but two of the most popular are the use of a chemically reduced silver film or silver paint.

APPLICATIONS OF ELECTROFORMING

Although electroforming is widely used in many industries, its importance and range of application is rarely appreciated, even by qualified engineers, scientists, and technologists. Similarly the ordinary "person in the street" has no idea of the extent to which they interface with electroformed goods in everyday life.

When the average person wakes up in the morning, he or she may step out of bed onto a carpet printed using electroformed screen-printing cylinders, look at wallpaper, and put on clothes made from fabric similarly patterned. That first cup of coffee may be filtered through an electroformed mesh, the first morning cigarette will have been manufactured using a number of electroformed products, and many electric razors use electroformed foils. Any electronic device—radio, television, tape deck—switched on to aid the waking-up process will depend on electroformed copper foil used in the circuitry. In addition, any record or CD

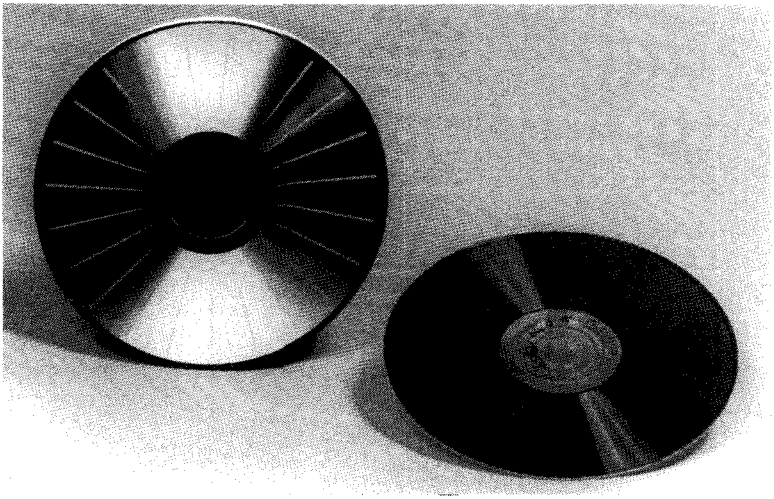


Fig. 2. Electroformed nickel stamper and platinum-coated polycarbonate user-write optical read-out disk. (Photo courtesy of Plasmon Data Systems, Royston, England.)

will have been made with an electroformed master. A wallet or purse picked up before leaving home will probably contain bank notes printed from electroformed plates, as well as credit cards with security holograms made using electroformed masters. On entering most modern cars, the occupant may well be looking at a fascia panel molded into an electroformed mold. These examples make it obvious how relevant this technology is to modern living.

The whole range of uses of electroforming is far too large to cover in this summary of the process, so just a few of the more important and interesting examples have been selected.

Audio and Visual Disks

The audio record and, more recently, the CD are two of the most commonly recognized products where electroforming is a vital part of the manufacturing process. This technique has been used to produce sound-recording devices since the beginning of the present century—first, shellac disks; followed by polyvinylchloride-molded, "long-playing" records; and most recently CDs.

It has been necessary to refine the precision of the electroforming process in order to cope with the extreme accuracy of surface detail necessary for CD manufacture. As noted earlier, a CD bears a helical track with 30 billion depressions only 0.1 micrometer deep, 0.4–0.6 micrometer wide, and from 0.5 to 2.0 micrometers long. For good reproduction quality, these all need to be of the correct size and in precisely the right place on the track. The latest developments have increased the disk capacity eightfold to enable full-length color video recordings to be produced. Similar technology is used to produce computer "user-write" optical read-out disks of the type shown in Fig. 2.

Electroformed Foil Products

As noted earlier, copper foil production represents by far the biggest application of electroforming, consuming about 80,000 metric tons of metal per year. It used for the manufacture of printed circuit boards and has, therefore, formed the backbone of the whole electronics industry for over 30 years.

Fig. 3. Printing with electroformed nickel screen-printing cylinders. (Photo courtesy of Nickelmesh AG, Rudolfstetten, Switzerland.)

Nickel foil is also electroformed and used in resistance elements, printed circuit boards with welded connections, asbestos-free gaskets, and fire-resistant membranes. A specially blackened nickel foil is used to make solar energy absorbers.

Both nickel and copper foils are manufactured on cylindrical mandrels continuously rotating within a conforming anode arrangement. Electroforming represents the only economic method of producing thin, wide foils to the dimensional precision required for these applications.

Mesh Products

Electroformed mesh products—that is, foils with regular patterns of perforations—comprise the largest single use of nickel in electroforming. There is a range of applications such as coffee and sugar filters, electric razor foils, tobacco tapes, and powder sieves.

By far the single most commercially important use is the production of screen-printing cylinders. These consist of thin-walled (typically 100 micrometer) electroformed tubes, which are up to 250 mm in diameter and 8 meters in length. The pattern of holes formed in the surface dictates the design, which can be printed by ink forced from the inside to the outside of the rolls using doctor blades. Fig. 3 shows electroformed cylinders on a printing machine where they are used sequentially to apply the various component colors of the full design. Electroformed screen-printing cylinders are used extensively all over the world to produce wall papers, fabrics, and carpets.

Large Electroforms

Very large products can be made by electroforming. Molds used for the manufacture of plastics components formed by low-pressure processes, for example, glass-fiber–reinforced

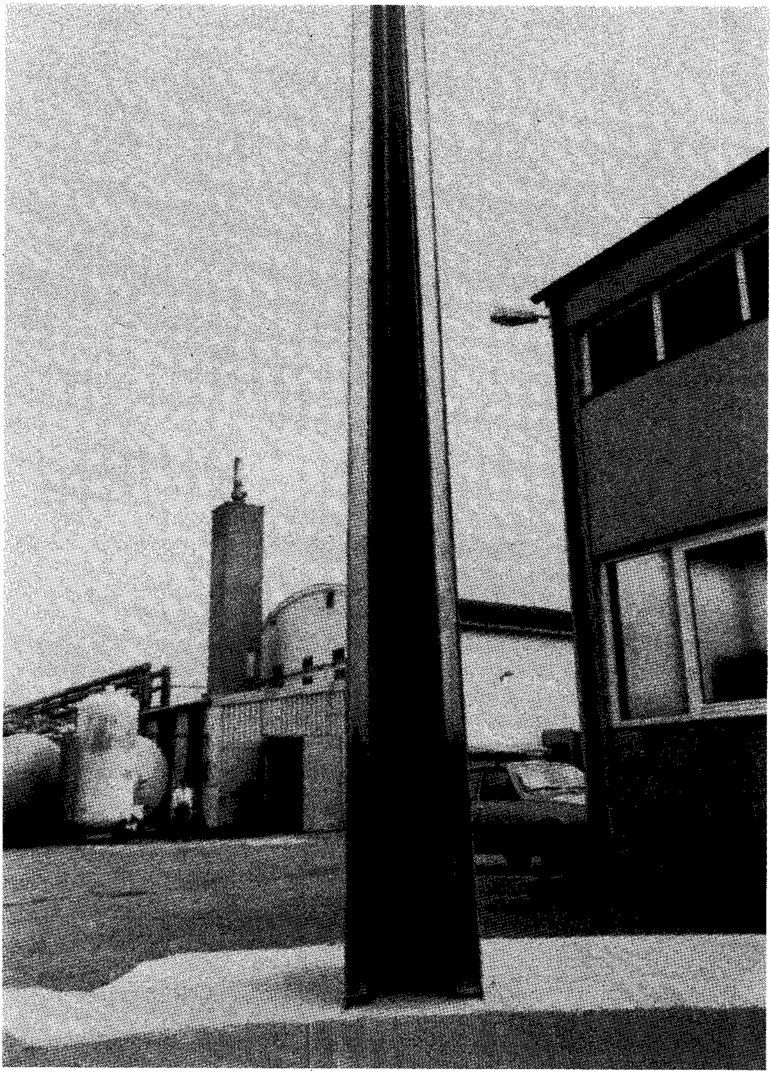


Fig. 4. Electroformed mold for wing fairings of the Airbus 320. (Photo courtesy of Galvanoform GmbH, Lahr, Germany.)

thermoset parts, are a good example. These are employed widely in the aerospace industry. A typical example is the mold for a large wing fairing being shown in Fig. 4. (The building

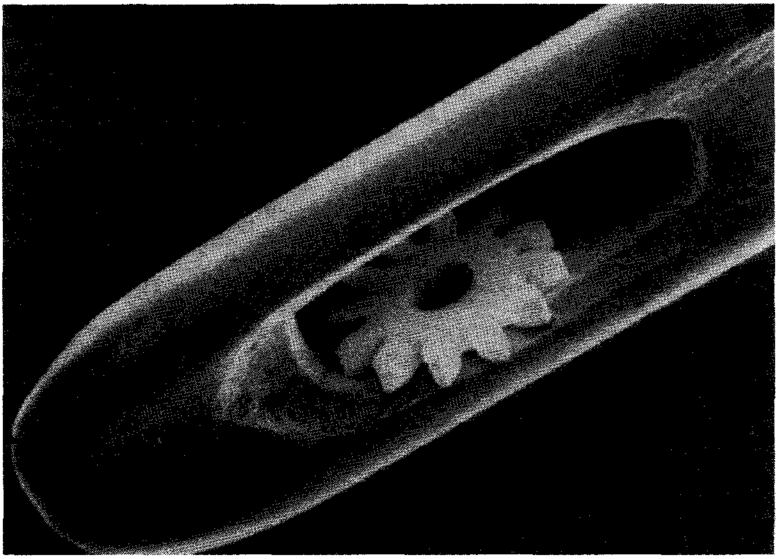


Fig. 5. Gear wheel produced by LIGA process. (Photo courtesy of CLRC Laboratory, Daresbury, England.)

in the background demonstrates the scale of the component.) Large electroformed molds are also used in the automotive industry for the production of one-piece moldings for the drivers' cabs of trucks.

Small Electroforms

In recent years, a new branch of electroforming has enabled extremely small components to be produced by electroforming. This technology, developed originally in Germany, is known as the LIGA process, its name being derived from the German acronym, LIthographie, Galvanoformung, und Abformung. The tiny products that can be made by this process are demonstrated by Fig. 5, which shows a perfectly formed, 12-tooth gear wheel small enough to be contained within the eye of an ordinary needle.

The LIGA process is being developed as part of much larger programs of microengineering. Almost all major industries have potential uses for these miniature or microcomponents, with automotive, aerospace, and medical applications already in place. In the medical industry, for example, electroformed components are used to manufacture very small electric motors, which can be passed along arteries to scour the walls, removing deposits that cause blocking of the artery and restrict blood flow.

MECHANICAL PLATING

by Gordon M. Allison

MacDermid Inc., Waterbury, Conn.

Mechanical plating is a room-temperature method that uses kinetic energy to deposit metal coatings on parts. The process is also known as impact plating or peen plating. Thin coatings of less than 25 μm (1 mil) are known as mechanical plating and heavier coatings up to 110 μm, as mechanical galvanizing.

The process uses open "cement mixer"-type tumbling barrels, to provide the necessary mixing and tumbling action. Parts to be coated are tumbled with glass beads, water, surface preparation chemicals, promoter chemicals, and metal powders. The chemical conditioners remove oxides from the coating metal surface. Rotational energy from the barrel causes the small metal particles to "peen" or cold weld together, first on the surface of the metal part, and then to previously bonded particles, until the required plating thickness is achieved. Coating bond development is caused by the deformation of the metal spheroids that expose clean active surfaces, allowing the particles to be cold welded into an atomic bond.

The mechanical plating process is nearly 50 years old. The original process, using citric acid, necessitated long process times (1–2 hr), and yielded poor coating efficiency. Wastewater treatment problems were caused by the chelated chemistry.

Today's coating systems are based on mineral acid, the process times are shorter (between 20 and 45 min), and the coating efficiency is above 90%. The waste is unchelated and simple to treat to common standards.

The process is used primarily to give ferrous-based parts coatings of zinc, tin, aluminum, and alloys or mixtures of these metals in various combinations. Coatings containing aluminum and zinc are one of the newer processes and approach the corrosion resistance of cadmium. Other soft, ductile metals such as brass, copper, lead, gold, silver, and indium can also be plated, although commercial applications are limited. Cadmium is easily plated, but its use has almost vanished.

One unique property of mechanical plating is the ability to deposit combination coatings, alloys, and layered or sandwich coatings. For example, when zinc and tin are mixed, the coating has better corrosion resistance in salt spray because of the lower galvanic potential of the mixed coating. When tin is layered over zinc, white corrosion products are reduced and the coating has a lower coefficient of friction. This allows the user to substitute this type of coating as a cadmium replacement.

Applicable specifications include ASTM B 695, B 696, MIL C-81562, plus many automotive and industrial specifications.

APPLICABLE PARTS

Mechanical plating of less than 25 μm (1 mil) coating thickness, finds wide use in the automotive industry on hardened (greater than Rockwell C 32) steel parts, and as a replacement for electroplating, because of freedom from hydrogen embrittlement problems. Spring steel parts found in appliances and electrical components are examples of other good candidates for the process.

Mechanical galvanizing has gained wide acceptance as an alternative to hot-dip galvanizing on fasteners and other small components. Coatings of 25 μm (1 mil) or greater are used for extended outdoor corrosion protection. The uniformity of the coating and the elimination of stickers, parts that are welded together, are primary benefits. This is not true for small parts handled in bulk using hot-dip methods. Corrosion resistance is equivalent to hot-dip galvanized coatings and quite often is improved because of better uniformity.

The suitability of parts for mechanical galvanizing is determined by part size and shape. Parts less than 300 mm (12 in.) and less than 1 kg (2 lb) are suitable for the process. Larger parts can be handled, but it is mostly a matter of cost due to reduced parts loading. Blind holes and deep recesses may make the part unsuitable. To obtain a satisfactory coating, solution and glass media must flow freely across the surface of the part so that sufficient energy is transferred through the glass beads. Media must be chosen that will not lodge in holes and recesses. Parts that are good candidates for mechanical plating include screws, bolts, nuts, washers, J-nuts, U-clips, and self-tapping screws. Parts suitable for mechanical galvanizing include structural bolts, washers, nuts, nails, pole line hardware, conduit hardware, and chain hardware.

Various substrates that are suitable for the mechanical plating process include high-carbon heat-treated spring steel, case- hardened or carbonitrided steel, leaded steel, high-strength low alloy steel, low-carbon steel, malleable iron, and sintered steel. Powder metallurgy is possible to plate without impregnation if the density is above a minimum of about 83%. Some stainless alloys such as 400 series are easily plated, and 300 series can be coated using special cycles. The process can also coat zinc die castings, brass, copper, and sintered copper. Because of the scrubbing action of the glass beads, it can be easier to mechanical plate than electroplate.

PROCESS DESCRIPTION

The processes for mechanical plating and galvanizing are similar. The sequence consists of adding oil-free parts to glass beads, water, surface preparation chemicals, promoters or accelerators, and additions of fine spherical metal powders. A standard recipe is followed based on surface area of the load of parts. Heavily soiled parts are best handled in an off-line cleaning setup. This decreases the water used and greatly adds to the productive time of the plating barrel. The process is continuous once started. The chemicals are additive, that is, the ingredients of the previous chemical are necessary to maintain the proper plating conditions. The steps are outlined below.

Surface Conditioning or Preparation

Surface conditioners contain mineral acids, wetting agents, and inhibitors to prevent attack on sound metal. The surface is activated, derusted, and descaled by the action of the conditioner and scrubbing of the media. The conditioner provides the proper pH for the plating reaction. The second step in conditioning consists of a copper flash, which serves to clean the parts and media further. The copper provides a heavier barrier to hydrogen and a more consistent metal surface that minimizes differences in the metallurgy of the substrate material. The process time for these steps is about 3–10 min for the surface conditioner and 3–5 min for the coppering stage.

Promoter or Accelerator

The promoter serves to clean the metal powder and control the size of the metal powder agglomerates that form. It also acts as a catalyst or accelerator to the coating process, controlling the coating efficiency and uniformity. Time for the promoter to mix or dissolve is 1–2 min.

Flash or Seed Coating

The small amount of zinc calculated to react with the promoter is called the flash or seed. This amount of metal produces sites for adhesion of subsequent metal powder additions. The surface changes from copper color to white during this step. This occurs in 3–5 min.

Table I. Metal Amount to Produce a Specified Coating Thickness on a Given Surface Area

	Metal Powder Weight	
Metal Powder Type	*lb/0.0001 in./100 ft^2*	*g/µm/m^2*
Zinc	0.40	7.7
Tin	0.42	8.1
Zinc/Tin (70%/30%)	0.41	8.0
Cadmium	0.50	9.6
Copper	0.51	9.8
Lead	0.65	12.5

Metal Powder Additions

Metal powder in the range of 4 to 10 µm diameter is added in increments. The number of additions affects the coating smoothness and uniformity. Smaller frequent additions for [illegible] of 5 µm (0.0002 in.) are normal, each addition requiring 1–3 min. The metal powder can also be added in the form of an aqueous slurry, helping to improve the uniformity. The amount of metal to produce a given thickness on a given surface area is shown in Table I.

The cycle is completed within 25–45 min depending on the thickness and part type. The structure or morphology of the coating consists of distorted shapes of metal particles that have been slightly flattened into football or dish shapes. The particles have been atomically bonded or cold welded from both their clean oxide-free environment in the solution and pressure from the adjacent parts and glass beads. The energy is controlled by varying the barrel angle and rotation speed. Usually, lighter parts require more energy and heavier parts less.

Media Mixes and Glass Beads

Glass beads or impact media are an important component of the mechanical process. Glass mixes are chosen that provide cushioning between the parts. Media form an energy transfer system. Media sizes are selected to both cushion and reach into recesses and corners plus thread roots on screw products. Neglect of media, as to amount and composition, is responsible for 90% of the problems in mechanical plating. Media mixes consist of two or more sizes of glass in the range of 200 µm (0.0008 in.) to 6 mm (0.24 in.) diameter. When the media amount drops, parts will scrape on each other causing poor adhesion, scratched coatings, and thin-edge problems. If an excess of media becomes crushed, it will be abrasive and wear the coating off as fast as it is put on. A guide to troubleshooting is given in Table II.

EQUIPMENT

A mechanical plating system is an engineered material handling system consisting of weighing, loading the plating barrel, media handling, parts separation, and drying. The coatings may be chromated in the same way as with electroplating. The coating barrel is the most important component. It is multisided and generally constructed of stainless steel with an impervious lining of synthetic or natural rubber or abrasion-resistant plastic. Variable speed and angle are part of the design. Hydraulic pumps and motors are the chief means of powering most systems.

Equipment in the 1950s and 1960s had a volume of 1–4.5 ft^3. Today's equipment ranges in size from 6 to 40 cubic feet of useable volume.

Table II. Troubleshooting Mechanical Plating Faults

Symptom	*Probable Causes*	*Corrective Action*
No plating; parts; practically bare all over.	1. Improper amount of surface conditioners and promoters used.	Check for proper charge of surface conditioners and promoter to plate amount of surface area of the load.
	2. Contamination of parts and media by oil.	Check parts after surface conditioning for water break. Use offline cleaning if possible.
	3. Parts are made of stainless steel or other alloy that will not condition or plate.	Contact supplier's technical service for special procedures that may be applicable.
	4. Surface conditioners unable to remove degree of oxide present on parts using standard time cycle and procedure.	Try adding surface conditioner first, letting barrel run for 5 min, then adding coppering agent and letting barrel run for 15 min.
Coatings end up thinner than expected	1. Insufficient metal powder used.	Coatings may be built up by additional metal powder. On future loads of this part type, recheck material usage for proper loading, increasing the amount if needed.
	2. Water temperature too low.	Coating may be built up as above. Check temperature of media return water. If it differs from recommendations, check for lack of a hot water supply.
	3. Excessive water levels.	Coatings may be built up as above. Higher than normal water levels have the effect of diluting the chemicals. Results will be the same as when not enough chemicals are used.
	4. Accumulation of metal contamination of the media.	Any metal in the media will accept plating; parts, chips, and filings or fine balls of plating metal. Use magnets to trap magnetic material. Affected run may be built up by adding more metal powder.
	5. Build up of fractured fine media.	Coatings may be built up as above. Too much fractured media in the media charge will cause the media to become very abrasive so that it will abrade the coatings off as fast as they are applied. Avoid putting media back into the batch out of sewers, catch basins, etc., until the fractured fines are removed by washing them through a screen fine enough to hold the smallest fraction of media that belongs in the media charge.

Table II. Troubleshooting Mechanical Plating Faults *(cont.)*

Symptom	*Probable Causes*	*Corrective Action*
	6. Oil contamination in the barrel.	Coatings must be stripped and parts, barrel, and media cleaned.
	7. Insufficient media or media out of balance.	Coatings will tend to be thinnest on edges and coverage very spotty when the problem is at its worst. Coatings can usually be built up once media charges are corrected. Weigh and analyze media charge.
	8. Plating metal deposited excessively on interiors, leaving outside edges thin.	Decrease water level or increase plating temperature.
Parts plate, but the coatings are poorly adherent, partially chipping off	1. Poor cleaning; incomplete removal of oil, rust, scale, or other surface soils.	Parts must be stripped, reconditioned, and replated. On future runs, check for correct temperature of the load, proper water level before adding surface conditioners, proper quantity of conditioners, and full conditioning time. Check parts for scale removal and water break.
	2. Inadequate coppering.	Parts must be stripped, reconditioned, and replated. If some parts copper well, and others do not, either the mixing was poor, causing the first parts to be exposed to deplete the copper in solution, or cleaning was incomplete. If no parts copper well, try adding conditioning preparations. If there is little improvement, the parts were not thoroughly cleaned before conditioning. Excessive metal contamination of the media can also cause problems by depleting the coppering solution.
	3. Sulfur contamination of the copper coating.	Presence of resulfurized steel in parts load will cause sulfide coating on copper surfaces that cause poor plating adhesion. High sulfur parts cannot be plated with the regular mechanical system.
	4. Poor mixing in the barrel.	Parts must be stripped, reconditioned, and replated. If parts tumble upon each other with no media present atop the load, this can cause poor adhesion and chipped coatings. Check for low media charge. If the parts will still not all mix in with the load of media, the parts loading on this part type must be decreased.

Table II. Troubleshooting Mechanical Plating Faults *(cont.)*

Symptom	*Probable Causes*	*Corrective Action*
	5. High water temperature.	Parts must be stripped, reconditioned, and replated. High water temperature during plating causes too rapid plating. Check temperature of load before adding surface conditioners. Add cold water and siphon off excess water if necessary.
	6. Loss of fine media.	Parts must be stripped, reconditioned, and replated after media is brought up to proper analysis.
	7. Attempt to plate too heavily with single adds of metal powder.	Parts must be stripped, reconditioned, and replated. When attempting to plate thicknesses more than 0.00035 in., the metal powder should be added in equal increments at 2–5 min. intervals, each increment containing metal powder to plate 0.0002 in. maximum. The last charge should run 10–15 min.
	8. Insufficient water in the plating barrel.	Parts must be stripped, reconditioned, and replated. Check parts for cleanliness before plating by making sure that clean water will run off in an even film without breaking up into droplets on the surface of the part (water-break test). To plate successfully, there must be some free water in the barrel to provide a good fluidity to the mass.
	9. Surface contamination by unsuitable detergents or rust inhibitors.	Parts must be stripped, reconditioned, and replated. Only nonionic cleaners only should be used to degrease parts. In addition, many rust inhibitors leave hard-to-remove films that will also cause poor plating adhesion.
Deeply scratched coatings with copper showing.	1. Parts scratched each other during plating because they have protruding sharp points or corners.	Parts may be built up by a second add of metal powder. Second addition should fill the scratches. Future runs on such part types should use a multiadd system for metal powder.
	2. Insufficient media.	Parts may be built up by a second add of metal powder after additional media is charged. Check size of media charge before the next load is run.
Poor coverage in corners, thread roots, and small recessed areas.	1. Loss of fine media.	Try another add of metal powder after replenishing fine media. Check analysis of media before next batch is run.
	2. Inadequate cleaning in recesses	Parts will require stripping, reconditioning, and replating. On future loads, clean prior to conditioning, checking after conditioning for signs of scale in recesses.

Table II. Troubleshooting Mechanical Plating Faults *(cont.)*

Symptom	*Probable Causes*	*Corrective Action*
Poor coverage inside drawn or cup-shaped parts.	1. Insufficient media fluidity	Try plating with high water level.
	2. Too rapid plating	Use two or more adds of metal powder or lower water temperature.
	3. Media formulation not suitable for part type	Generally, better results are obtained from the use of media batches containing a recommended media mix.
Parts plate well, have good adhesion, but have a poor polish.	1. Media out of balance	Check weight and analysis of media.
	2. Low plating temperature	Check temperature of load at start of surface conditioning, reset temperature regulator if necessary.
	3. Oil contamination during plating	Check parts for cleanliness before plating by making sure that clean water will run off in an even film without breaking into droplets on the surface of the part (water-break test).
	4. Insufficient plating time	Try increasing the plating time to improve polish.
Coatings are lumpy, although they have good adhesion, coverage, and polish.	1. Water temperature too high during plating.	Check temperature of water; reset mixing valve if necessary.
	2. Media imbalance	Check media analysis, particularly for the smallest fraction.
	3. Too much metal powder plated too fast.	Try increasing number of metal powder adds.
	4. Insufficient or incorrect promoter	Use a more inhibited promoter.
Coatings may vary considerably in thickness from part to part, with generally good adhesion. Thickly plated parts may be lumpy in appearance.	1. Carryover of detergent from degreasing operation	Improve rinsing of parts before charging them into the barrel.
	2. Poor distribution of metal powder in barrel	Add metal powder only to the liquid pool when the barrel is running. Try to add as uniformly as possible, using small scoops instead of dumping it all in one spot.
	3. Excessive amounts of metal added at once	Plating controlling agents can only handle metal powder for 0.0003 in. thickness or less at once. If additions are too large, the dispersion is inadequate and thickness will vary excessively.
	4. More than recommended quantity of metal powder used for a flash coat.	Use recommended quantities, no more.

Table III. Plating Capacities for Typical Parts, lb

	Nails				*Cap Screws*				*Nuts*			*Flat Washers*		
Unit Size, ft³	*6 d Comm*	*10 d Comm*	*16 d Comm*	*1¼ Roof*	*¼ × 1 in*	*½ × 2 in.*	*¾ × 3 in.*	*1 × 6 in.*	*½ in.*	*¾ in.*	*1 in.*	*⅜ in.*	*⅝ in.*	*⅞ in.*
6	500	300	275	400	750	660	600	300	750	650	650	675	600	525
10	875	500	475	750	1250	1100	1000	500	1250	1125	1125	1125	1000	875
20	1750	1000	950	1500	2500	2200	2000	1000	2500	2250	2250	2250	2000	1750
30	2625	1500	1425	2250	3750	3300	3000	1500	3750	3375	3375	3375	3000	2625
40	3500	2000	1900	3000	5000	4400	4000	2000	5000	4500	4500	4500	4000	3500

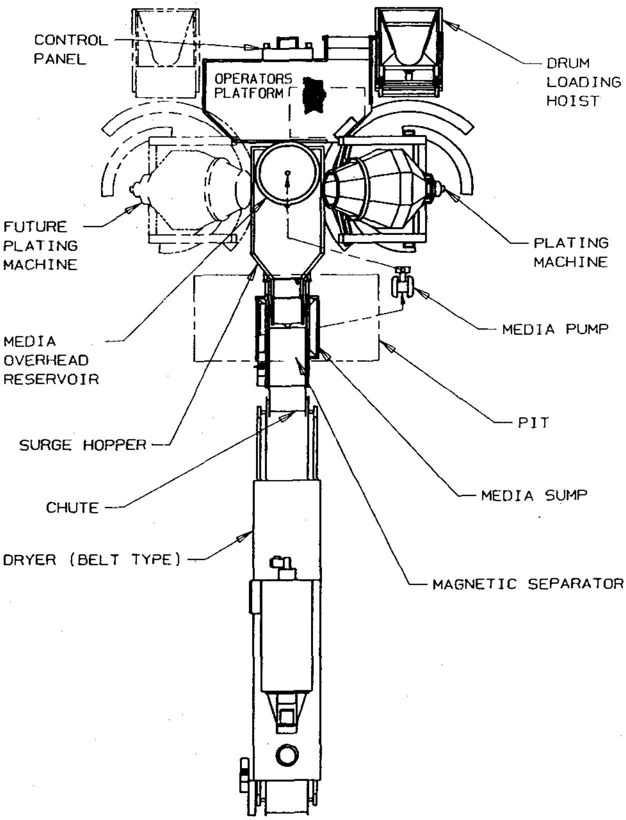


Fig. 1. Typical mechanical galvanizing system layout.

Table III shows that as the machine grows in volume, the load size increases in proportion. There is no increase in labor input when going to a larger size barrel. The largest sizes will be the most economical to run.

A means must be provided for weighing the load of parts and then transferring them into the plating barrel. After discharge from the plating barrel, the parts are accumulated in the surge hopper/separator, which receives the entire batch of parts and media. Parts are separated automatically and media accumulated in the media handling system. A second charge of media is available so that the barrel can be reloaded while the previous batch is being separated. In this way, the barrel is always available for plating. After separation, the parts can be chromated in a continuous chromating module, and finally dried in a conveyorized oven. Figure 1 shows a typical mechanical galvanizing system in plan view. This system is the same as a mechanical plating system. An optional chromate module can be placed between the separator and the dryer. The dryer can be a mesh belt as shown or a vibrating type sometimes called a toss/catch action type.

Mechanically deposited plate can be chromated and sealed or lubricated in the same fashion as electroplate. The surface accepts chromates, chromates and dyes, or phosphates readily.

The equipment cost for a mechanical plating/galvanizing installation will be 25–35% of a similar capacity electroplating installation. Coatings can be applied cost effectively by mechanical plating. Parts coated will be free of hydrogen embrittlement. This will further reduce costs by eliminating the need for an embrittlement relief baking.

PHYSICAL VAPOR DEPOSITION (PVD) PROCESSES

by Donald M. Mattox

Society of Vacuum Coaters, Albuquerque, N.M.

Physical vapor deposition (PVD) processes are deposition processes in which atoms or molecules of a material are vaporized from a solid or liquid source, transported in the form of a vapor through a vacuum or low-pressure gaseous environment, and condense on a substrate. PVD processes can be used to deposit films of elemental, alloy, and compound materials as well as some polymeric materials. Typically, PVD processes are used to deposit films with a thickness range of a few angstroms* to thousands of angstroms. Typical PVD deposition rates vary from 10–100 Å/sec. PVD processes have the advantage that almost any inorganic material and many organic materials can be deposited using pollution-free deposition processes. The deposits can be of single materials, layers with a graded composition, multilayer coatings, or very thick deposits.

PVD processes can be categorized as follows:

Vacuum evaporation—material from a thermal vaporization source reaches the substrate without collision with gas molecules in the space between the source and substrate.

Sputter deposition—source of vaporized material is a surface (target) being subjected to physical sputtering. As far as film properties are concerned sputter deposition should be further subdivided into high- and low-pressure sputter deposition.

Arc vapor deposition—uses a high current, low-voltage electric arc in a low-pressure gas to erode the solid cathodic electrode by a moving arc or to melt and evaporate the anodic electrode.

Ion plating—utilizes concurrent or periodic bombardment of the depositing film by atomic-sized energetic particles to modify and control the composition and properties of the depositing film. Ion plating can use vacuum evaporation sputtering or arc vaporization as the source of the depositing material. Ion beam assisted deposition (IBAD) uses a high-energy ion beam to bombard the depositing film with inert or reactive ions to modify the film properties and, in the case of a reactive ion, to enhance chemical reactions. Figure 1 summarizes the various PVD processes.

Films of compound materials are deposited by vaporizing the compound material (e.g., silicon monoxide) or by having the depositing material react with an ambient gaseous environment, such as oxygen or nitrogen, or a codeposited species, such as carbon or silicon, to form films of compound materials such as titanium nitride, zirconium nitride, silicon dioxide, titanium carbide, titanium carbonitride, tungsten silicide, etc. In many cases the codepositing species comes from the plasma decomposition of a chemical vapor precursor species such as a hydride, chloride, or fluoride. This reaction-type processing is often used as an adjective, i.e., reactive sputter deposition or reactive ion plating.

VACUUM EVAPORATION

Vacuum evaporation is a PVD process in which material from a thermal vaporization source reaches the substrate without collision (i.e., a long mean free path) with gas molecules in the space between the source and substrate. The trajectory of the vaporized material is, therefore, line-of-sight. The vacuum environment also provides the ability to reduce gaseous contamination in the deposition system to any desired level. Typically, vacuum evaporation

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*1 angstrom (Å) = 10^{-10} meters = 0.1 manometers (nm) = 10^{-4} microns (μm) = 0.004 microinches.

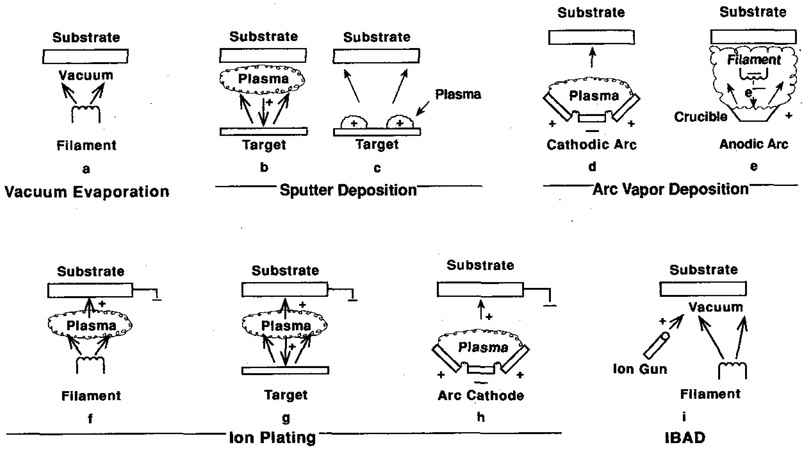

Fig. 1. PVD processing techniques: (a) vacuum evaporation with a resistively heated filament, (b) sputter deposition in a plasma environment, (c) sputter deposition with a confined plasma, (d) cathodic arc vapor deposition, (e) anodic arc vapor deposition with a thermoelectron source, (f) ion plating with a filament vaporization source, (g) ion plating with a sputtering source, (h) ion plating with an arc source, and (i) ion beam assisted deposition (IBAD) in a vacuum environment.

takes place in the pressure range of 10^{-5} Torr** to 10^{-9} Torr, depending on the level of gaseous contamination that can be tolerated in the resulting deposited film. Figure 2 depicts a simple vacuum evaporation/deposition arrangement using a resistively heated filament vaporization source and depicts the principal components of the deposition system.

The substrate fixturing is an important deposition component. Fixturing allows the substrate(s) to be held in a face-down position so that particulates do not settle on the surface causing pinholes in the film, provides a means for heating the substrate, and allows movement during deposition that is important to obtaining a uniform deposition over the substrate surface. The shutter is an important component in that it allows the vaporization source to be heated without exposing the substrate to volatile contaminant material that may vaporize from the source first. It also minimizes radiant heating from the vaporization source. By opening and closing the shutter, the deposition time can be accurately controlled. The "glow bar" allows the formation of plasma in the system for in situ cleaning of the substrate surface in the deposition chamber.

The equilibrium vapor pressure is an important property of the material to be thermally vaporized. In a closed container at equilibrium as many atoms return to the surface as leave the surface and the pressure above the surface is the equilibrium vapor pressure. Vapor pressures are strongly dependent on the temperature as is shown in Figure 3. The vaporization rate from a hot surface into a vacuum (free surface vaporization rate) depends on the temperature and the equilibrium vapor pressure of the material at that temperature. Materials with a high vapor pressure at low temperatures are typically vaporized from resistively heated sources. Refractory materials, which require a high temperature to vaporize, require the use of focused high-energy electron beam heating for vaporization.

**Standard atmospheric pressure = 760 mm mercury (or Torr) or 1.01×10^5 newtons per meter square (or pascals). 1 torr = 10^3 milliTorr (mTorr). 1 mTorr = 7.5 pascals (pa) = 1 (mm of mercury).

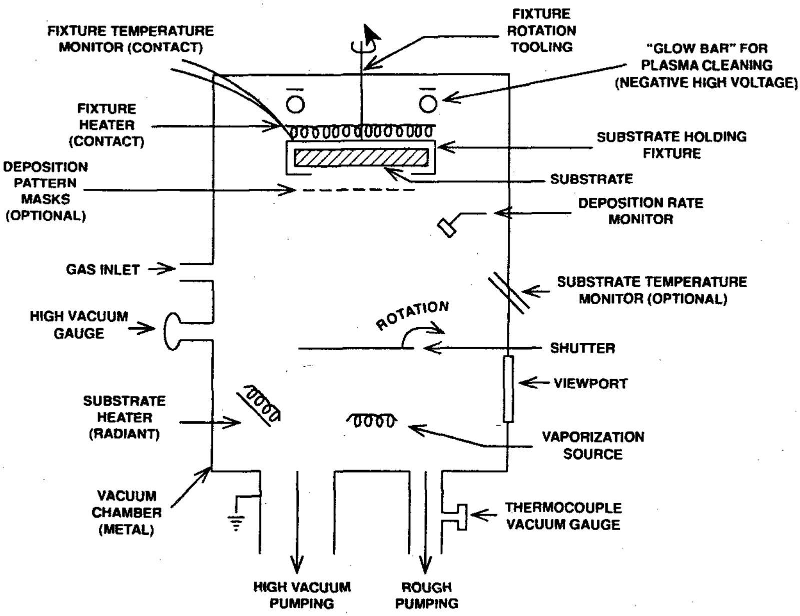

Fig. 2. Principal components of a vacuum evaporation system.

For vacuum evaporation, a reasonable deposition rate can be obtained only if the free surface vaporization rate is fairly high. A vapor pressure of 10^{-2} Torr (approximately 10^{-3} g/cm^2/sec free surface vaporization rate) is typically considered the value necessary to provide a useful deposition rate. Materials with that vapor pressure above the solid are described as subliming materials (e.g., chromium, carbon), and materials with that vapor pressure above the liquid are described as evaporating materials. Many materials, such as titanium, can be deposited either by sublimation or evaporation, depending on the temperature of the source. For alloys the vaporization rate of each constituent is proportional to the relative vapor pressures (Raoult's Law); therefore, during vaporization, the higher vapor pressure material will vaporize more rapidly, and the source will be progressively enriched in the lower vapor pressure material as evaporation progresses.

Most elements vaporize as atoms but some, such as antimony, carbon, and selenium, have a portion of their vapor as clusters of atoms. For these materials special vaporization sources called baffle sources can be used to ensure that the depositing vapor is in the form of atoms by causing the material to be vaporized from multiple hot surfaces before it leaves the source.

Some compounds, such as silicon monoxide, silicon nitride, hafnium carbide, tin dioxide, boron nitride, lead sulfide, and vanadium dioxide, sublime. The molecules of many compound materials partially dissociate on vaporization; however, some may vaporize primarily as molecules. Notable among the materials that vaporize without much molecular dissociation are silicon monoxide and magnesium fluoride, which are widely used in optical coating technology. The degree of dissociation of a compound depends strongly on the vaporization temperature. When depositing a compound that dissociates, the depositing film is generally deficient in the gaseous constituent. For example in the evaporation of silicon dioxide (SiO_2) the resulting film is deficient in oxygen giving an

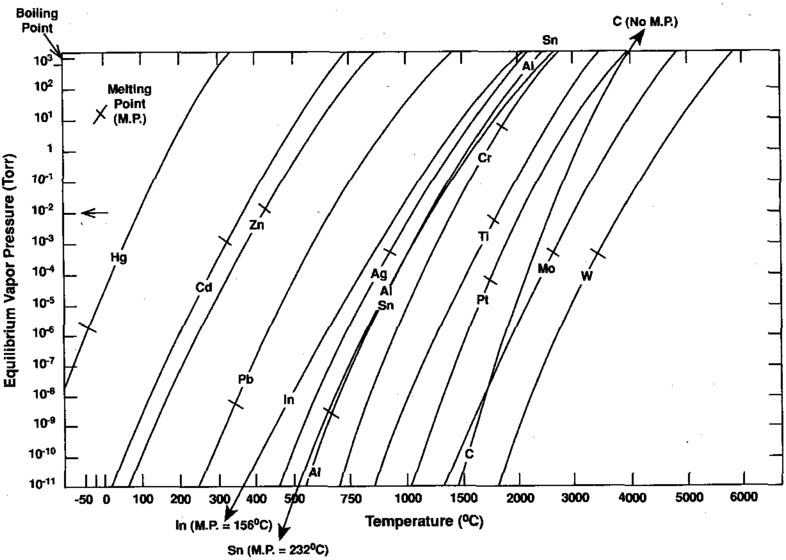

Fig. 3. Equilibrium vapor pressure of some selected materials.

SiO_{2-x}, composition film, which has a brownish color. This loss of gaseous constituents during vaporization can be partially compensated for by using reactive evaporation or activated reactive evaporation, where there is a low-pressure reactive gas or plasma of reactive gas in the deposition environment, or by continuous reactive ion bombardment of the depositing material from an "ion gun." This type of deposition is also called quasi-reactive deposition.

For low vaporization rates the material from a point vaporization source deposits on a substrate with a distance-and-substrate-orientation dependence given by the cosine deposition distribution. Figure 4 shows the distribution of atoms vaporized from a point source and the thickness distribution of the film formed on a planar surface above the point source based on the cosine distribution equation.

In actuality the flux distribution from the source may not be cosine but can be modified by source geometry, collisions in the vapor above the vaporizing surface when there is a high vaporization rate, level of evaporant in the source, changes of vaporization source geometry with time, etc. Evaporation rates are typically monitored in situ and in real time by collecting the vapor on the surface of a quartz crystal oscillator, causing the oscillation frequency to change. Calibration allows the change in frequency to be related to deposited film mass and thickness.

The strong dependence of deposition rate on geometry and time often requires that fixturing and tooling be used to randomize the substrate(s) position during deposition in order to increase the film thickness uniformity. This fixturing also randomizes the angle of incidence of the depositing vapor flux, thereby increasing the uniformity of the film properties over the substrate(s) surface.

Advantages of vacuum evaporation:

- High-purity films can be deposited from high-purity source material.
- Source of vaporized material may be a solid in any form and purity.
- High vaporization rates can be attained.

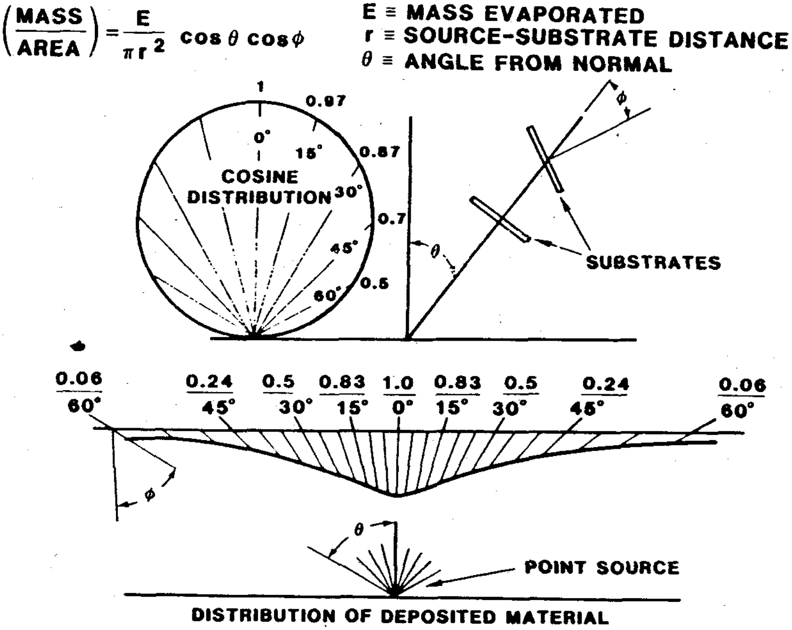

Fig. 4. Cosine distribution of vapor from a point source.

- The line-of-sight trajectory and limited-area sources allow the use of shutters and masks.
- Deposition monitoring and control are relatively easy.
- Deposition system can be pumped at a high rate during the deposition.
- Residual gases and vapors in the vacuum environment are easily monitored.
- Probably the least expensive of the PVD processes.

Disadvantages of vacuum evaporation:

- Many alloy compositions and compounds can only be deposited with difficulty.
- Line-of-sight and limited-area sources result in poor surface coverage on complex surfaces without proper fixturing and fixture movement.
- Line-of-sight trajectories and limited-area sources result in poor film thickness uniformity over large areas without proper fixturing and fixture movement.
- Few processing variables are available for film property control.
- Source material utilization may be poor.
- High radiant heat loads can exist in the deposition system.

Vacuum evaporation is used to form optical interference coatings, mirror coatings, decorative coatings, permeation barrier films on flexible packaging materials, electrically conducting films, and corrosion-protective coatings.

SPUTTER DEPOSITION

Sputter deposition is the deposition of particles vaporized from a surface by the physical sputtering process. Physical sputtering is a nonthermal vaporization process where surface atoms are physically ejected by momentum transfer from an atomic-sized energetic bombarding particle, which is usually a gaseous ion accelerated from a plasma or ion gun. If the surface atom that has been struck attains enough energy it will shake other atoms in the near-surface region and a "collision cascade" will develop. Multiple collisions can result in some momentum being directed back toward the surface and, if the energy attained by a surface atom, which is struck from below, is sufficient, it can be physically ejected from the surface, i.e., sputtered. Most of the energy that is transferred by the bombarding particle appears as heat in the near-surface region.

At all but the lowest bombarding energies the flux of atoms that are sputtered from the surface leaves the surface with a cosine distribution. They typically have average kinetic energies higher than that of thermally vaporized atoms and have a high energy "tail" in the energy distribution that can be several tens of eV.***

The sputtering yield is the number of surface atoms that are sputtered for each incident energetic bombarding particle. The sputtering yield depends on the bombarding particle energy, relative masses of the bombarding and target species, the angle of incidence of the bombarding species, and the chemical bond strength of the surface atoms. The most common inert gas used for sputtering is argon (MW = 40). Figure 5 shows the sputtering yields from several materials sputtered with argon ions at various energies. As the angle of incidence of the bombarding particles becomes off-normal, the sputtering yield can increase 2 to 3 times, up to a point where the bombarding particles transfer little momentum because of the high collision angle and the sputtering yield drops off rapidly. Under these conditions most of the bombarding species are reflected from the surface. The apparent sputtering yield can be affected by the surface topography since, in sputtering a rough surface, some of the sputtered particles are "forward sputtered" and redeposited on the surface.

Since the sputtering process removes each solid surface atomic layer consecutively, if there is no diffusion, the composition of the vapor flux leaving the surface is the same as the composition of the bulk of the material being sputtered. This allows the sputter-vaporization of alloy compositions, which cannot be thermally evaporated because of greatly differing vapor pressures of the constituents.

Often, surfaces to be sputtered have a surface layer composed of a reacted material such as an oxide or nitride. Since the chemical bonding of the compound materials is stronger than that of the elemental material the sputtering yield is initially low until the surface layer is removed. Also, if reactive gases are present, they can continuously "poison" the target surface by forming compounds on the surface, giving low sputtering yields.

Particles that are sputtered or reflected from the sputtering target surface at low gas pressures will travel in a line-of-sight path, with no gas-phase collisions to condense on or bombard the substrate. If the gas pressure is higher, gas-phase collisions can take place, thus reducing the energy of the particles and scattering them from a line-of-sight path. If there are enough collisions the energetic particles are "thermalized" to the energy (temperature) of the ambient gas. Energetic gaseous particles bombarding the surface of the growing film can affect the film-formation process and the properties of the deposited film material. Thus, it makes a difference in film properties whether the sputter deposition is done at a low gas pressure or a higher gas pressure.

The most simple plasma configuration is "DC diode sputtering" where a high negative DC voltage is applied to a conductive surface in a gas, a plasma is formed, which fills the container, and positive ions are accelerated to the surface.

In the DC diode glow discharge the electric field strength is high near the cathode and most of the applied voltage is "dropped" across a region near the surface called the cathode dark space. This region is the primary region of ionization. The rest of the space between the cathode and anode, which is often grounded, is filled with a plasma where

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***An electron volt (eV) of energy is the amount of energy attained by a singly charged particle accelerated through a potential of 1 V. A kinetic energy of one eV is equivalent to a thermal temperature of ~11,000°C.

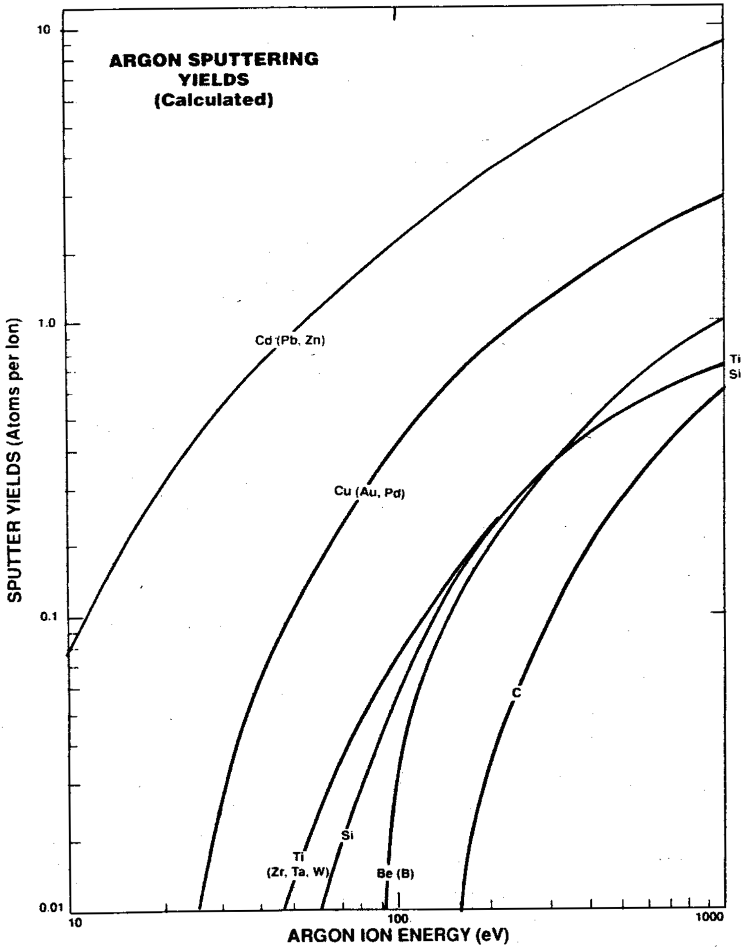


Fig. 5. Sputtering yield of several materials bombarded with argon ions at various energies. The materials listed parenthetically have similar sputtering yield curves.

there is little potential gradient. In the cathode dark space region, ions are accelerated from the plasma to impinge on the target surface with a high kinetic energy. This ion bombardment causes the ejection of secondary electronics, which are accelerated away from the cathode and cause ionization and atomic excitation by electron-atom collision. At equilibrium enough electrons are created to cause enough ions to create the electron flux needed to sustain the discharge. The DC diode plasma is generally weakly ionized with perhaps one ion to 10^4 neutrals, and it has an average particle temperature of several electron volts.

Typically, a DC diode argon sputtering plasma will be operated at 10–20 mTorr gas pressure. At this pressure, the cathode dark space will have a width of ~1 cm. If a ground surface comes within a cathode dark space distance of the cathode the plasma will be extinguished between the two surfaces. This means that ground shields can be used to localize the plasma discharge to regions of the cathode where sputtering is desired. The equipotential field lines around the cathode surface are conformal over flat or gently curved surfaces but curve sharply around the edges and underneath the ground shields. Ions are accelerated normal to the field lines, which gives uniform bombardment over most of the target surface, but where there is appreciable field curvature, focusing of the ion will give high erosion rates.

In the DC diode configuration, the ions that impinge on the target surface do not have the full cathode fall potential since the gas pressure is high enough to give charge-exchange collisions and "thermalization" (momentum transfer) collisions between the accelerating ions and the residual gas neutrals. This creates a flux of ions and high energy neutrals with a spectrum of energies that impinge on the target surface. The higher the gas pressure, the less the mean energy of particles that impinge on the target. Since the mean energy is much less than the applied voltage, typically 1,000 to 5,000 V is used for DC sputtering even though 500 eV particles are quite effective for sputtering. At typical DC sputtering pressures energetic particles reflected or sputtered from the target surface are thermalized to lower energies before they strike a surface; however, the electrons that are accelerated away from the cathode can attain high energies and bombard surfaces giving heating, which can be undesirable. Typically, DC diode sputtering discharges are controlled by the sputtering gas pressure and the target power in Watts per cm^2. Since most of the bombarding energy is given up as heat the sputtering target must be actively cooled, usually with flowing, chilled deionized water.

Reactive or contaminant gases in a plasma become activated by excitation, dissociation, or fragmentation of molecules to form radicals, ions, and excited species. These activated species react with the target surface, giving poisoning of the target by forming compounds on the target surface. The formation of an electrically conductive compound, such as titanium nitride, on the target surface will reduce the sputtering yield significantly, while the formation of an electrically insulating layer, such as titanium dioxide, will cause surface charging and the DC glow discharge will be extinguished. Activation of contaminant species in the plasma also increases contamination of the deposited film material.

The DC diode sputtering configuration has the advantage that large areas can be sputtered rather uniformly over long periods of time, the target can be made conformal with the substrate, and the target material is well utilized. In addition the DC diode plasma, which fills the entire deposition chamber, can be used to plasma clean surfaces as a part of the in situ cleaning. Disadvantages of DC diode sputter deposition include the rather low sputtering rate, target poisoning by reactive contaminants, surface heating due to the accelerated electrons accelerated away from the target, and that only electrical conductors can be used as sputtering targets.

Simple DC diode sputtering can best be used to deposit relatively unreactive metals such as gold, copper, and silver. Since most of these materials can also be deposited by thermal evaporation this type of DC sputter deposition has not been widely used. In recent years the advent of the use of magnetic fields to confine the plasma near the target surface, increase the plasma density, and increase the sputtering rate has allowed the use of "DC diode magnetron sputtering" to be used to deposit metals and compound materials at high rates. In the reactive sputter deposition of compound materials, such as titanium nitride, the target is eroded so rapidly that the target is not poisoned by the reactive gas used to form the compound film material.

Magnetron sputtering configurations use a magnetic field (~200 gauss), usually from permanent magnets near the target (cathode) surface, to confine the electrons near the surface. When an electron is ejected from the target surface, it is accelerated away from the surface by the electric field, but it is forced to spiral around the magnetic field lines. The EXB force causes the electron to also move normal to the EXB plane and, if the magnetic field is arranged appropriately, the electrons will form a closed-path circulating current near the surface. This closed circulating path can be easily produced on a planar surface or any surface of revolution such as a cylinder, cone, hemisphere, etc.

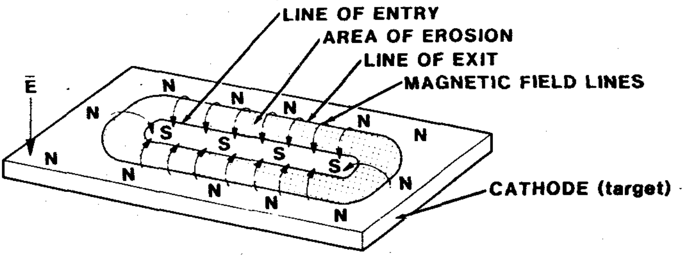


Fig. 6. DC diode planar magnetron sputtering configuration.

By confining the electrons near the surface, the DC gas discharge can be sustained at low pressures where collision and charge-exchange collision probabilities are low. This allows the applied cathode potential to be low (<1,000 V) with a high-energy high-current ion flux, which gives a high sputtering yield and high sputtering rates. The various magnetron sputtering configurations are the most widely used sputter deposition configurations. Figure 6 shows a planar magnetron configuration.

In the planar magnetron configurations the sputter-erosion is nonuniform and, in the case of the planar magnetron, the erosion pattern looks like an elongated racetrack, which, for a long narrow target, has an erosion pattern giving two parallel line sources of vaporized material. This means that the deposition pattern is nonuniform and film thickness uniformity must be accomplished by substrate (or target) movement. In the case of the planar magnetron this is often done by passing flat substrates on a pallet over the two line sources. The nonuniform erosion also means that the target material utilization can be poor. Utilization is often improved by shaping the magnetic field, moving the magnets, or moving the target material over the magnets.

Confining the plasma to near the target surface also means that the plasma does not fill the space between the source and the substrate and is not available for plasma activation of reactive species for reactive sputter deposition, or as a source of ions for sputter cleaning or bias sputter deposition. A plasma can be formed in the source-substrate space by utilizing an rf potential on the sputtering target along with the DC potential, by establishing an auxiliary discharge near the substrate, or by using an "unbalanced" magnetron configuration where some of the electrons ejected from the target surface are allowed to escape by having a portion of the magnetic filed normal to the target surface.

In reactive sputter deposition, where reactive gases or gas mixtures are used, the gas pressure and composition are important. Too high a reactive gas pressure can result in poisoning the target surface, with an associated reduction in sputtering rate. Too low a gas pressure can result in not enough reaction with the depositing film, resulting in an undesirable film composition. Unbalanced magnetron sputtering is particularly useful in reactive sputter deposition; however, the plasma generated in various regions near the target by the unbalanced configurations is generally nonuniform in plasma properties because of the nonuniform escape of the electrons from the target region.

When coating three-dimensional parts the magnetron and unbalanced magnetron targets are often arranged so that the parts to be coated are passed between opposing targets. This allows deposition on all sides of the parts even though the average angle of incidence of the depositing material varies over the surface of the part. This variation in angle of incidence can cause a variation in the properties of the film deposited. To minimize this variation the part can be rotated in front of the magnetron target(s). When using facing unbalanced magnetron targets it is best to have the north unbalanced field of one target be opposite the south unbalanced field of the other target.

Advantages of sputter deposition:

- Elements, alloys, and compounds can be sputtered and deposited.
- The sputtering target provides a long-lived vaporization source with a stable geometry.
- In some configurations the sputtering target provides a large-area vaporization source that can be of any shape.
- In some configurations the sputtering source can be a defined shape such as a line or a rod.
- In some configurations reactive deposition can be easily accomplished using reactive gaseous species that are activated in a plasma (i.e., reactive sputter deposition).

Disadvantages of sputter deposition:

- Sputtering rates are low compared with those that can be attained in thermal evaporation.
- In many configurations the deposition flux distribution is nonuniform and requires fixturing to randomize the position of the substrates in order to obtain films of uniform thickness and properties.
- Sputtering targets are often expensive and material utilization may be poor.
- Most of the energy incident on the target turns into heat, which must be removed.
- Generally, the pumping speed of the system is reduced during sputtering and gaseous contamination is not easily removed from the system.
- Gaseous contaminants are activated in the plasma, thus making film contamination more of a problem than in vacuum evaporation.
- In some configurations radiation and bombardment from the plasma or sputtering target can degrade the substrate.

Film formation by sputter deposition was first reported by Wright in 1877, and Edison patented a sputter deposition process for depositing silver on wax phonograph cylinders in 1904. Sputter deposition is widely used to deposit thin film metallization on semiconductor material, energy-controlling coatings on architectural glass, transparent conductive coatings on glass, reflective coatings on compact disks, magnetic films, dry film lubricants, wear-resistant coatings, and decorative coatings.

ARC VAPOR DEPOSITION

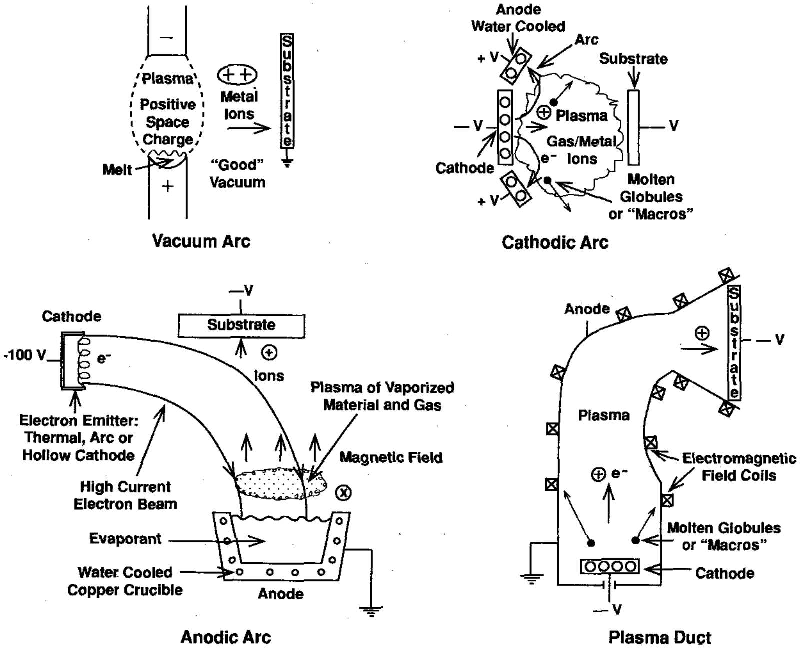
In arc vapor deposition the vapor to be deposited is formed from the anode or cathode of a low-voltage high-current DC arc, in a low-pressure gaseous atmosphere. In cathodic arc vaporization, which is the most common PVD arc vaporization process, the high current density arc moves over a solid cathodic electrode causing local heating and vaporization. The arc movement may be random or "steered" using a magnetic field. In many cathodic arc vapor deposition systems multiple cathodic arc sources are used to give deposition over large areas.

In anodic arc vapor deposition, electrons melt and vaporize the anodic electrode. The electrons for the anodic arc can come from a number of sources such as a hot hollow cathode, a hot thermoelectron emitting filament, or from ion bombardment. The configuration of an anodic arc vapor deposition system is similar to that of an E-beam thermal evaporation system.

An arc can also be ignited in a vacuum forming a vacuum arc. In the vacuum arc the electrodes must be closely spaced and a positive space charge is generated in the space between the electrodes. This space charge repels positively charged ions to high energies. Figure 7 shows some vacuum arc vaporization techniques.

In arc vaporization the atoms that are vaporized pass through a high-density electron cloud and many if not most of the atoms become ionized. These "film-ions" can then be accelerated to high energies by an electric field in the low-pressure gas. The electrons in the arc also ionize the gaseous ambient and those ions can also be accelerated to high energies in an electric field. If some of the gaseous ions are of a reactive gas then a compound material, such as a nitride, can be deposited.

In cathodic arc vaporization some of the material is ejected as molten globules called "macros." These macros deposit on the film material and create bumps, which, when dislodged, create pinholes. Some materials are more prone to form macros than are others.



Vacuum Arc

Cathodic Arc

Anodic Arc

Plasma Duct

Fig. 7. Arc vapor deposition: vacuum arc, cathodic arc, anodic arc, and plasma duct.

The macros can be eliminated by using a plasma duct as shown in Figure 7. In the plasma duct a magnetic field bends the electrons and the film-ions follow the electrons to keep volumetric charge neutrality in the plasma. The macros are deposited on the duct walls rather than on the substrate.

Advantages of arc vapor deposition–anodic arc:

- Formation of "film-ions" allow them to be accelerated to high energies.
- The arc plasma "activates" reactive species and makes them more chemically reactive.
- A high vaporization rate can be attained.
- Macros are not formed.

Advantages of arc vapor deposition–cathodic arc:

- Formation of "film-ions" allow them to be accelerated to high energies.
- The arc plasma "activates" reactive species and makes them more chemically reactive.
- Alloy materials can be vaporized readily.
- Low radiant heat loads in the system.
- Solid vaporization surfaces allow placement of sources in any position in the system.

Disadvantages of arc vapor deposition–anodic arc:

- High radiant heat loads in the system.
- Molten material limits positioning of source(s) in the system.

Disadvantages of arc vapor deposition–cathodic arc:

- The formation of "macros" can be a determining factor in some materials and applications.

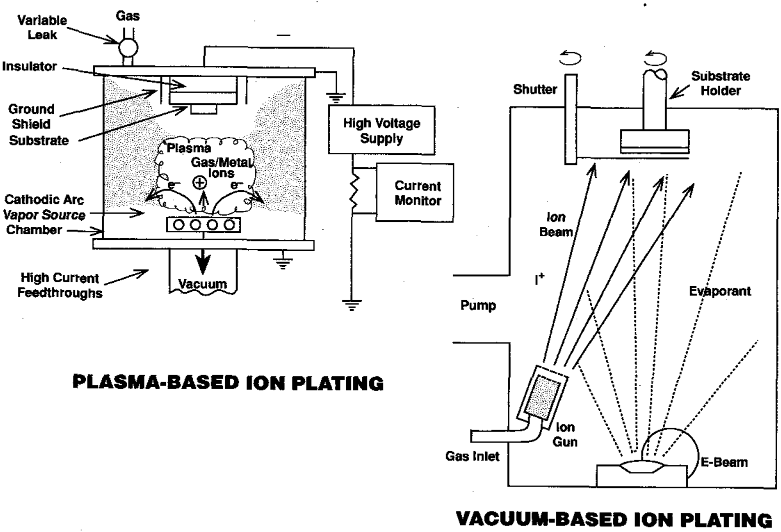


Fig. 8. Plasma-based ion plating using a cathodic arc source and a negatively biased substrate, and vacuum-based ion plating when bombardment is with ions that are accelerated away from an ion gun.

Cathodic arc vapor deposition is used in depositing wear-resistant decorative/functional coatings, such as TiN (gold-color) and ZrN (brass-color), on a variety of substrates such as plumbing fixtures and door hardware. Anodic arc vapor deposition is used to deposit adherent elemental materials, such as chromium and diamond-like carbon, for wear resistance and compound materials for optical coating applications.

ION PLATING

In the early 1960s it was shown that controlled concurrent energetic bombardment of the depositing film material by particles of atomic or molecular dimensions could be used to modify and tailor the properties of the deposited film material. Thus, concurrent or periodic bombardment during deposition can be a major PVD processing variable. Ion plating utilizes concurrent or periodic energetic particle bombardment of the depositing film material to modify and control the composition and properties of the depositing film. In ion plating, the source of material to be deposited can be evaporation, sputtering, arc erosion, laser ablation, or other vaporization source. The energetic particles used for bombardment are usually ions of an inert or reactive gas; however, when using an arc erosion source, a high percentage of the vaporized materials is ionized and ions of the film material can be used to bombard the growing film. Ion plating can be done in a plasma environment where ions for bombardment are extracted from the plasma, or it may be done in a vacuum environment where ions for bombardment are formed in a separate ion gun. The latter ion-plating configuration is often called ion beam assisted deposition (IBAD). Figure 8 shows examples of plasma-based and vacuum-based ion plating configurations.

The most common form of ion plating is the plasma-based process where the substrate and/or its fixture is an electrode used to generate a DC or rf plasma in contact with the surface being coated. If an elemental or alloy material is being deposited the plasma can be of an inert gas, usually argon. In reactive ion plating, the plasma provides ions of reactive species, such as nitrogen, oxygen, or carbon (from a hydrocarbon gas), that are accelerated to the surface to form compounds such as oxides, nitrides, carbides, or carbonitrides. Typically, in plasma-based ion plating, the substrate fixture is the cathode of the DC circuit; however, the plasma can also be formed independently of the substrate and ions are accelerated from the plasma to the surface of the growing film.

Concurrent or periodic bombardment during film growth modifies the film properties by affecting the nucleation of the depositing atoms, densifying the film by compaction or "atomic peening," by introducing significant thermal energy directly into the substrate surface region, and by sputtering and redeposition of the film material. Energetic particle bombardment can also introduce compressive film stress by recoil implantation of surface atoms into the lattice structure and, in the case of reactive deposition, enhancing chemical reactions on the surface by bombardment-enhanced chemical reactions and sputtering/desorbing untreated species. In the case of reactive deposition in plasma-based ion plating or ion sources using a plasma of reactive species, the plasma also activates the reactive species, which enhances the kinetics of chemical reactions at the surface.

It has been determined that for argon ion bombardment the energy of the bombarding ions should be greater than ~50 eV and less than ~300 eV to effectively modify the film properties. For lower ion energies, momentum transfer is not sufficient to displace the film atoms, and for higher energies, the bombarding species will be incorporated into the film unless the substrate temperature is high. This gas incorporation can result in void formation and microporosity in the film. To completely disrupt the columnar growth morphology in deposited films of refractory materials requires that ~20 eV per depositing atom be added by the concurrent bombardment. This means that a bombardment ratio of about one energetic ion (200 eV) per I0 depositing film atoms is used. For example, at a 30 Å/sec deposition rate, the ion flux of 200 eV ions should be at least 10^{15} ions/cm^2/sec or an ion current (singly charged ions) of ~0.1 mA/cm^2. At these ion energies and fluxes an appreciable portion (10–30%) of the depositing atoms are sputtered from the growing film surface giving a growth rate less than the deposition rate.

Generally, in ion plating, the high-energy bombarding, particles are positively charged ions that are extracted from a plasma and accelerated to the crowing film surface, which is at a negative potential with respect to the plasma or the ion, and are extracted and accelerated from an ion gun. In plasma-based ion plating, the negative potential on the substrate surface can be formed by applying a continuous DC potential to an electrically conductive surface, applying a pulsed DC or rf potential to an insulating surface, by applying a combination of DC and rf bias, or by inducing a "self bias" on an electrically insulating or electrically "floating" surface. When using an ion gun the high energy ions can be injected into a field-free region so that a negative potential does not have to be applied to the substrate to achieve high energy bombardment of the surface.

Concurrent bombardment during film growth affects nearly all film properties such as the film-substrate adhesion, density, surface area, porosity, surface coverage, residual film stress, index of refraction, and electrical resistivity. In reactive ion plating, the use of concurrent bombardment allows the deposition of stoichiometric, high-density films of compounds such as titanium nitride and zirconium nitride at low substrates.

Advantages of ion plating:

- Significant energy is introduced into the surface of the depositing film by the energetic particle bombardment.
- Surface coverage can be improved over vacuum evaporation and sputter deposition due to gas scattering and sputtering/redeposition effects.
- Controlled bombardment can be used to modify film properties such as adhesion, film density, residual film stress, optical properties, etc.
- Film properties are less dependent on the angle of incidence of the flux of depositing material than with sputter deposition and vacuum evaporation due to gas scattering, and sputtering/redeposition and atomic peening effects.

- In reactive ion plating, the plasma can be used to activate reactive species and create new chemical species that are more readily adsorbed so as to aid in the reactive deposition process.
- In reactive ion plating, bombardment can be used to improve the chemical composition of the film material by "bombardment-enhanced chemical reactions" (increased reaction probability) and the sputtering of unreacted species from the growing surface.

Disadvantages of ion plating:

- It is often difficult to obtain uniform ion bombardment over the substrate surface leading to film property variations over the surface.
- Substrate heating can be excessive.
- Under some conditions, the bombarding gas may be incorporated into the growing film.
- Under some conditions, excessive residual compressive film stress can be generated by the bombardment.
- In plasma-based ion plating, the system pumping speed is sometimes limited, thus increased film contamination problem.

Ion plating is used to deposit hard coatings of compound materials, adherent metal coatings, optical coatings with high densities, and conformal coatings on complex surfaces.

VACUUM DEPOSITION PROCESSING EQUIPMENT

An integral part of the vacuum deposition process is the vacuum equipment used to generate the deposition environment. The principle parts of the deposition system are the deposition chamber and fixturing, which holds the parts to be coated and the vacuum pumping system, which removes gases and vapors from the deposition chamber. The generation of a vacuum has two purposes: one is to reduce the gas pressure enough so that vaporized atoms have a long "mean free path" and do not nucleate in the vapor to form "soot," and the second is to reduce the contamination level to the point that an adherent film of the desired chemical composition can be deposited.

The fixturing holds the substrate(s) that are to be coated and provides the motion, relative to the vaporization source, that is often necessary to give a uniform deposition over a large area or over many substrates. The fixture along with the "cycle time" of the system determines the product throughput of the process. The deposition chamber is sized so as to contain the fixturing and provide room for accessories such as shutters, deposition rate monitors, heaters, etc. Proper design, construction, operation, and maintenance of the deposition system is necessary to obtaining a reproducible product with high yield and desired product throughput.

SUMMARY

Each of the PVD processes discussed has its advantages and disadvantages. Each requires different process monitoring and controlling techniques. Generally, the most simple technique and configuration that will give the desired film properties and most economical product throughput should be used. There are no "handbook values" for the properties of deposited thin films and the properties depend on the details of the deposition process. In order to have a reproducible process and product it is important to have good process controls.

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ELECTROLESS (AUTOCATALYTIC) PLATING

by James R. Henry

Wear-Cote International, Rock Island, Ill.

Electroless plating refers to the autocatalytic or chemical reduction of aqueous metal ions plated to a base substrate. The process differs from immersion plating in that deposition of the metal is autocatalytic or continuous.

THE ELECTROLESS BATH

Components of the electroless bath include an aqueous solution of metal ions, reducing agent(s), complexing agent(s), and bath stabilizer(s) operating in a specific metal ion concentration, temperature, and pH range.

Unlike conventional electroplating, no electrical current is required for deposition. The electroless bath provides a deposit that follows all contours of the substrate exactly, without building up at the edges and corners. A sharp edge receives the same thickness of deposit as does a blind hole.

The base substrate being plated must be catalytic in nature. A properly prepared workpiece provides a catalyzed surface and, once introduced into the electroless solution, a uniform deposition begins. Minute amounts of the electroless metal (i.e., nickel, copper, etc.) itself will catalyze the reaction, so the deposition is autocatalytic after the original surfaces are coated. Electroless deposition then continues, provided that the metal ion and reducing agent are replenished. If air or evolved gas, however, are trapped in a blind hole or downward facing cavity, this will prevent electroless deposition in these areas.

In electroless plating, metal ions are reduced to metal by the action of chemical reducing agents, which are simply electron donors. The metal ions are electron acceptors, which react with electron donors. The catalyst is the workpiece or metallic surface, which accelerates the electroless chemical reaction allowing oxidation of the reducing agent. During electroless nickel deposition, byproducts of the reduction, orthophosphite or borate and hydrogen ions, as well as dissolved metals from the substrate, accumulate in the solution. These can affect the performance of the plating bath. As nickel is reduced, orthophosphite ions (HPO_3^{2-}) accumulate in the solution and at some point interfere with the reaction. As the concentration of orthophosphite increases, there is usually a small decrease in the deposition rate and a small increase in the phosphorus content of the deposit. Ultimately, the accumulation of orthophosphite in the plating solution results in the precipitation of nickel phosphite, causing rough deposits and/or spontaneous decomposition.

The metal ion and reducer concentration must be monitored and controlled closely in order to maintain proper ratios, as well as the overall chemical balance of the plating bath. The electroless plating deposition rate is controlled by temperature, pH, and metal ion/reducer concentration. Each of the particular plating reactions has optimum ranges at which the bath should be operated (Table I). A complexing agent(s), also known as a chelator, acts as a buffer to help control pH and maintain control over the "free" metal salt ions available to the solution, thus allowing solution stability. The stabilizer(s) acts as a catalytic inhibitor, retarding potential spontaneous decomposition of the electroless bath. Few stabilizers are used in excess of 10 ppm, because an electroless bath has a maximum tolerance to a given stabilizer. The complexing agent(s) and stabilizer(s) determine the composition and brightness of the deposit. Excessive use of stabilization material(s) can result in a depletion of plating rate and bath life including poor metallurgical deposit properties.

Trace impurities and organic contamination (i.e., degreasing solvents, oil residues, mold releases) in the plating bath will affect deposit properties and appearance. Foreign inorganic

Table I. Typical Plating Bath Components and Operating Parameters

Electroless Bath	*Temperature*	*pH*	*Deposition Rate/hr*	*Metal Salt(s)*	*Reducing Agent(s)*	*Complexing Agent(s) or Chelators*	*Stabilizer(s)*	*pH Adjustment*
Acid nickel	77–93°C (170–200°F)	4.4–5.2 (medium P) (high P) 6.0–6.5 (low P)	12.7–25.4 μm (0.5–1 mil)	Nickel sulfate Nickel chloride	Sodium hypophosphite Sodium borohydride Dimethylamine borane (DMAB)	Citric acid Sodium citrate Succinic acid Proprionic acid Glycolic acid Sodium acetate	Fluoride compounds Heavy metal salts Thiourea Thioorganic compounds (i.e., 2-mercaptobenzothiazole, MBT) Oxy anions (i.e., iodates)	Ammonium hydroxide Sulfuric acid
Alkaline nickel	26–95°C (79–205°F)	8.5–14.0	10–12.7 μm (0.4–0.5 mil)	Nickel sulfate Nickel chloride	Sodium borohydride Sodium hypophosphite DMAB Hydrazine	Citric acid Sodium citrate Lactic acid Glycolic acid Sodium acetate Sodium pyrophosphate	Thiourea Heavy metal salts Thioorganic compounds Triethanolamine Thallium salts Selenium salts	Ammonium hydroxide Sulfuric acid Sodium hydroxide
Copper	26–70°C (79–158°F)	9.0–13.0	1.7–5 μm (0.04–0.3 mil)	Copper sulfate Copper acetate Copper carbonate Copper formate Copper nitrate	Formate Formaldehyde DMAB Sodium hypophosphite	Rochelle salt EDTA Ammonium hydroxide Pyridium-3-sulfonic acid Potassium tartrate Quadrol	Thiodiglycolic MBT Thiourea Sodium cyanide Vanadium pentoxide Potassium ferrocyanide	Hydrochloric acid Sulfuric acid Sodium hydroxide Potassium hydroxide
Gold	65–88°C (149–190°F)	10.0–13.0	2–5 μm (0.08–0.2 mil)	Gold cyanide Gold chloride Potassium aurate	DMAB Sodium hypophosphite Potassium borohydride Potassium cyanoborohydride	Sodium phosphate Potassium citrate Sodium borate Potassium tartrate EDTA	Alkali metal cyanide Alkali hydrogen fluoride Acetylacetone	Potassium hydroxide Phosphoric acid Sulfuric acid
Palladium	45–73°C (113–165°F)	8.0–12.0	2–5 μm (0.08–0.2 mil)	Palladium chloride Palladium bromide	Sodium hypophosphite DMAB Triethylamine borane	Ammonia Methylamine EDTA	Thioorganic compounds Organic cyanides Thiourea Thiocyanates	Ammonium hydroxide Hydrochloric acid
Cobalt	85–95°C (185–203°F)	9.0–11.0	2.5–10 μm (0.1–0.4 mil)	Cobalt chloride Cobalt sulfate	DMAB Sodium hypophosphite	Sodium citrate Citric acid Ammonium chloride Succinic acid	Urea Thioorganic compounds	Ammonium hydroxide Sodium hydroxide

Table II. Alkaline Electroless Nickel-Phosphorus Bath

Nickel sulfate	30 g/L
Sodium hypophosphite	30 g/L
Sodium pyrophosphate	60 g/L
Triethanolamine	100 ml/L
pH	10.0
Temperature	30–35°C (86–95°F)

ions (i.e., heavy metals) can have an equal effect. Improper balance and control will cause deposit roughness, porosity, changes in final color, foreign inclusions, and poor adhesion.

ELECTROLESS NICKEL

The most widely used engineering form of electroless plating is, by far, electroless nickel. Electroless nickel offers unique deposit properties including uniformity of deposit in deep recesses, bores, and blind holes. Most commercial deposition is done with an acid phosphorus bath owing to its unique physical characteristics, including excellent corrosion, wear and abrasion resistance, ductility, lubricity, solderability, electrical properties, and high hardness.

Electroless nickel baths may consist of four types:

1. Alkaline, nickel-phosphorus.
2. Acid, nickel-phosphorus.
   a) 1–4% P (low phosphorus)
   b) 5–9% P (medium phosphorus)
   c) 10–13% P (high phosphorus)
3. Alkaline, nickel-boron.
4. Acid, nickel-boron.

The chemical reducing agent most commonly used is sodium hypophosphite (NaH_2PO_2); others include sodium borohydride ($NaBH_4$), or an aminoborane such as n-dimethylamine borane (DMAB) [$(CH_3)_2NHBH_3$]. Typical reactions for a hypophosphite reduced bath are as follows:

$$H_2PO_2^- + H_2O \rightarrow H^+ + HPO_3^{2-} + 2H \tag{1}$$

$$Ni^{2+} + 2H \rightarrow Ni + 2H^+ \tag{2}$$

$$H_2PO_2^- + H \rightarrow H_2O + OH^- + P \tag{3}$$

$$H_2PO_2^- + H_2O \rightarrow H^+ + HPO_3^{2-} + H_2 \tag{4}$$

Alkaline nickel-phosphorus deposits are generally reduced by sodium hypophosphite. These alkaline baths can be formulated at low temperatures for plating on plastics. Deposits provide good solderability for the electronics industry, and operating energy costs are reduced due to some solutions' low operating temperatures; however, less corrosion protection, lower adhesion to steel, and difficulty in processing aluminum due to high pH values are drawbacks. One such bath consists of the components shown in Table II.

An example of a high-temperature, alkaline, electroless nickel-phosphorus bath is given in Table III.

Acid nickel-phosphorus deposits normally consist of 87–94% nickel and 6–13% phosphorus, operating at 77–93°C (171–200°F), with a pH of 4.4–5.2. Low phosphorus electroless nickel baths contain 1–4% phosphorus and normally operate at 80–82°C (176–180°F), with a pH of 6.0–6.5. The reducing agent is commonly sodium hypophosphite.

Table III. High-Temperature, Alkaline Electroless Nickel-Phosphorus Bath

Nickel sulfate	33 g/L
Sodium citrate	84 g/L
Ammonium chloride	50 g/L
Sodium hypophosphite	17 g/L
pH	9.5
Temperature	85°C (185°F)

The resultant deposit melting point is 890°C (1,635°F) for 8–9% phosphorus baths and will vary dependent on the amount of phosphorus alloyed in the deposit. The pH of the solution is the controlling factor affecting the phosphorus content of the deposit. The higher the pH, the lower the phosphorus content, resulting in deposit property changes. Lower phosphorus-containing deposits (i.e., 1–3%) typically have less corrosion resistance than 10% alloys. Low phosphorus deposits do have good corrosion protection against alkaline solutions such as sodium hydroxide. Also, deposits containing phosphorus in excess of 8.0% are typically nonmagnetic. When the pH drops below 4.0, subsequent nickel deposition virtually stops.

As-deposited nickel-phosphorus hardness is 500–600 Vickers hardness number (VHN), and maximum values of 1,000 VHN may be realized by post–heat-treatment of the coating at a temperature of 399°C (750°F) for 1 hour. The temperature is a dominant factor in determining the final deposit hardness. Careful consideration should be given to the choice of temperature in order not to affect structural changes of the base substrate. Additionally, low temperatures are used (116°C/240°F) to relieve any hydrogen embrittlement that may be produced from pretreatment cycles or subsequent electroless nickel deposition.

Postbaking of the deposit produces marked structural changes in hardness and in wear and abrasion resistance. Depending upon the temperature, bath composition, and phosphorus content, this postbake cycle will totally change the initial amorphous structure, resulting in nickel phosphide precipitation creating a very hard matrix. Complete precipitation of nickel phosphides does not occur at temperatures significantly below 399°C (750°F). In general, deposits with 9.0% phosphorus and above tend to produce lower as-deposited hardness values, but give slightly higher hardness when post–heat-treated. The coating will discolor above 250°C (482°F) in an air atmosphere. Prevention of coating discoloration can be accomplished in a vacuum, inert, or reducing atmosphere oven. Physical properties affected by the post–heat-treatment include increasing hardness, magnetism, adhesion, tensile strength, and electrical conductivity while decreasing ductility, electrical resistivity, and corrosion resistance.

Thickness of the nickel-phosphorus deposit generally ranges from 2.5 to 250 μm (0.1–10.0 mil). Deposits less than 2.5 μm and greater than 625 μm are currently and successfully being performed. The latter being typical of repair or salvage applications. Thickness measurements can be carried out with electromagnetic devices (eddy current), micrometers, coulometrics, beta backscatter, and X-ray fluorescence.

Table IV gives an example of an acid hypophosphite-reduced bath.

Alkaline nickel-boron solutions utilize the powerful reducing agent, sodium borohydride, to produce a deposit containing 5–6% boron and 94–95% nickel by weight. These highly

Table IV. Acid Hypophosphite-Reduced Electroless Nickel Bath

Nickel sulfate	28 g/L
Sodium acetate	17 g/L
Sodium hypophosphite	24 g/L
Lead acetate	0.0015 g/L
pH	4.4–4.6
Temperature	82–88°C (180–190°F)

Electroless Nickel Plating

by W. Riedel 311 pages $130.00

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Table V. Sodium Borohydride-Reduced Electroless Nickel Bath

Nickel chloride	31 g/L
Sodium hydroxide	42 g/L
Ethylenediamine, 98%	52 g/L
Sodium borohydride	1.2 g/L
Thallium nitrate	0.022 g/L
pH	>13
Temperature	93–95°C (200–205°F)

alkaline solutions operate at a pH of 12.0–14.0 and temperatures of 90–95°C (195–205°F). These baths tend to be less stable because of their high alkalinity, and bath decomposition may occur if the pH falls below 12.0. Complexing agents such as ethylenediamine are used to prevent precipitation of nickel hydroxide. As-deposited hardness values of 650 to 750 VHN are typical. After post–heat-treatment at 399°C (750°F) for 1 hour, values of 1,200 VHN can be produced. The melting point of borohydride-reduced deposits is 1,080°C (1,975°F).

Table V gives an example of a sodium borohydride-reduced electroless nickel bath.

Acid nickel-boron varies from 0.1 to 4% boron by weight depending on the bath formulation. The boron content of electroless nickel is reduced by DMAB. Bath parameters include a pH of 4.8–7.5, with an operating temperature range of 65–77°C (149–171°F). DMAB-reduced deposits have a very high melting temperature of 1,350°C (2,460°F). Baths containing less than 1% boron have excellent solderability, brazing, and good ultrasonic (wire) bonding characteristics. A typical DMAB-reduced bath is given in Table VI.

ELECTROLESS COPPER

Electroless copper deposits are generally applied before electroplating on plastics and other nonconductors, providing a conductive base for subsequent plating. These include acrylonitrile butadiene styrene (ABS), polystyrene, modified polyphenylene oxide, polyvinyl chloride (PVC), Noryl, polyethylene, polysulfone, structural foam, epoxy, and ceramics. In such applications, usually a thin deposit (0.127 μm; 0.05 mil) is applied, followed by an additional decorative or protective thickness of copper, nickel, or gold deposited electrolytically or electrolessly. The electroless copper in such applications provides good life in corrosive atmospheric and/or environmental exposures.

Automotive, appliance, printed wiring boards, molded interconnect devices, plastic composite connectors, multichip modules, and EMI/RFI shielding of other electronic devices represent major markets for electroless copper. In through-hole plating of printed wiring boards, the use of electroless copper has eliminated the need for an electrodeposited flash and provides excellent electrical conductivity in these hard-to-reach areas.

In the pretreatment of circuit boards, the most common method involves an acidic aqueous solution of stannous chloride ($SnCl_2$) and palladium chloride ($PdCl_2$) immersion for

Table VI. Dimethylamine Borane-Reduced Electroless Nickel Bath

Nickel sulfate	25 g/L
Sodium acetate	15 g/L
n-Dimethylamine borane (DMAB)	4 g/L
Lead acetate	0.002 g/L
pH	5.9
Temperature	26°C (78°F)

Table VII. Formaldehyde-Reduced Electroless Copper Bath

Copper salt as Cu^{2+}	1.8 g/L
Rochelle salt	25 g/L
Formaldehyde as HCHO	10 g/L
Sodium hydroxide	5 g/L
2-Mercaptobenzothiazole (MBT)	< 2 g/L
pH	12.0
Temperature	25°C (77°F)

subsequent deposition of the electroless copper. Many proprietary activators are available in which these solutions can be used separately or together at room temperature. Palladium drag into the electroless copper bath can cause solution decomposition instantly.

The pH of an electroless copper bath will influence the brightness of the copper deposit. Usually a value above 12.0 is preferred. A dark deposit may indicate low bath alkalinity and contain cuprous oxide. The plating rate is equally influenced by pH. In formaldehyde-reduced baths a value of 12.0–13.0 is generally best. Stability of the bath and pH are critical. A high pH value (14.0) results in poor solution stability and reduces the bath life. Below 9.5, solution stability is good; however, deposition slows or ceases. The principal components of the electroless copper bath (copper, formaldehyde, and caustic) must be kept within specification through replenishment. Other bath chemical components will remain within recommended ranges. Complexing agents and stabilizer levels occasionally need independent control. Other key operating parameters include temperature, air agitation, filtration, and circulation.

Various common reducing agents have been suggested, however, the best known reducing agent for electroless copper baths is formaldehyde. The complexing agent (i.e., Rochelle salt) serves to complex the copper ion to prevent solution precipitation and has an effect on deposition rates as well as the quality of the deposit. These conventional baths are stable, have plating rates of 1–5 μm or 0.04–0.2 mil/hr, and operate in an alkaline solution (pH 10.0–13.0).

An example of a formaldehyde-reduced electroless copper bath is provided in Table VII.

Recent formulations allow for alkanol amines such as quadrol-reduced baths. These high build [>10 μm/hr >0.4 mil/hr)] or heavy deposition baths operate at a lower pH without the use of formaldehyde. High build baths generally are more expensive and exhibit less stability but do not have harmful formaldehyde vapors given off during subsequent solution make up, heating, and deposition. These baths can deposit enough low stress copper to eliminate the need for an electrolytic flash. Quadrol is totally miscible with water and thus is resistant to many conventional waste treatment procedures.

ELECTROLESS GOLD

There is a growing need in the electronics industry for selective plating to conserve plating costs and to allow the electronics engineer freedom for circuit design improvement.

Table VIII. Electroless Gold Bath

Gold hydrochloride trihydrate	0.01 M
Sodium potassium tartrate	0.014 M
Dimethylamine borane	0.013 M
Sodium cyanide	400.0 mg/L
pH (adjusted with NaOH)	13.0
Temperature	60°C (140°F)

Table IX. Electroless Palladium Bath

Palladium chloride	10 g/L
Rochelle salt	19 g/L
Ethylenediamine	25.6 g/L
Cool solution to 20°C (68°F) and then add:	
Sodium hypophosphite	4.1 g/L
pH (adjusted with HCl)	8.5 g/L
Temperature	68–73°C(155–165°F)

Many electronic components today are difficult to gold plate by electrolytic means. Thus, electroless gold is currently being used in the fabrication of semiconductor devices, connector tabs, chips, and other metallized ceramics. Most commercially available electroless gold deposits are produced first by plating a thin deposit of immersion gold, followed by electroless gold plating. There are a few true autocatalytic gold processes available with 99.99% purity.

Table VIII gives an example of an electroless gold bath.

Electroless gold can successfully be applied to Kovar, nickel, nickel alloys, electroless nickel, copper, copper alloys, electroless copper, and metallized ceramics. Electroless gold can be deposited onto already present thin electrodeposited gold to give added strength.

ELECTROLESS PALLADIUM

Electroless palladium deposits are ductile and ideal for contacts undergoing flexing (i.e., printed circuit board end connectors and electronic switch contacts). The deposit has also been used as a less expensive replacement for gold, providing tarnish resistance and solderability. Electroless palladium has been used to replace rhodium for wear applications.

Using specific bath components, the deposit can be hard and bond to electroless nickel with a bond strength greater than the tensile strength of the palladium plate itself. Metals such as stainless steel and nickel can be plated directly. Copper, brass, and other copper alloys require an electroless nickel preplate. The electroless nickel preplate can be either from a hypophosphite- or boron-reduced bath.

Table IX gives an example of an electroless palladium (hypophosphite-reduced) bath.

ELECTROLESS COBALT

Thin electroless cobalt deposits have use in the electronics industry on magnetic memory discs and storage devices primarily for their magnetic properties.

Table X gives an example of an electroless cobalt bath.

COMPOSITES AND POLYALLOYS

The uniform dispersion of micron or submicron particles in an electroless composite deposit will enhance the lubricity and the wear and/or abrasion resistance over base substrates

Table X. Electroless Cobalt Bath

Cobalt chloride	30 g/L
Sodium hypophosphite	20 g/L
Sodium citrate	35 g/L
Ammonium chloride	50 g/L
pH	9.5
Temperature	95°C (203°F)

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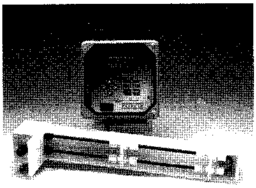

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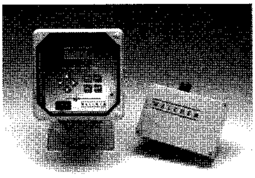

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and conventional electroless deposits. Composites containing fluorinated carbon (CF_x), fluoropolymers (PTFE), natural and synthetic (polycrystalline) diamonds, ceramics, chromium carbide, silicon carbide, and aluminum oxide have been codeposited. Most commercial deposition occurs with an acid electroless nickel bath owing to the unique physical characteristics available to the final codeposit. The reducing agent used may be either a hypophosphite or boron complex. For Lamellar solids, starting materials are naturally occurring elemental forms like coke or graphite. Fluorinated carbon (CF_x) is produced by reacting coke with elemental fluorine. The thermal stability of the CF_x class of solid lubricants is higher than PTFE, allowing the CF_x composite to be postbaked for maximum hardness (1,100 VHN). The CF_x composite exhibits high wear resistance coupled with a low coefficient of friction.

The inclusion of these finely divided particles within an electroless matrix (15–25% by volume) involves the need to maintain uniform dispersion of the occluded material during metal deposition. Specialized equipment is required and part size, configuration, and deposit thickness are limited. Deposition rates will vary, depending upon the type of electroless bath utilized. The surface morphology of the particle used (i.e., type, size, and distribution in the matrix) will greatly influence the final codeposit properties and composition. The coefficient of friction and wear resistance of the composite are related to particle size and concentration in the electroless bath.

Applications include food processing equipment, military components, molds for rubber and plastic components, fasteners, precision instrument parts, mating components, drills, gauge blocks, tape recording heads, guides for computers, and textile machine components.

Due to the resultant matrix surface topography (when using diamonds or silicon carbide, for example), the final surface roughness must be considered. Special postplate surface finish operations must be employed to regain the required rms (microinch) finish. In severe abrasion applications involving high pressure foundry molding, it has been noted that the softer electroless nickel matrix wears first, exposing harder silicon carbide particles, which create poor drawability of the resin/binder from the mold.

Polyalloys have been developed to produce deposits having three or four elements with specific coating properties. These include applications where unique chemical and high temperature resistance or electrical, magnetic, or nonmagnetic properties are requirements. The use of nickel-cobalt-iron-phosphorus polyalloys produce magnetic (for memory) properties. Other polyalloys include nickel-iron-phosphorus, nickel-cobalt-phosphorus, nickel-phosphorus-boron, nickel-iron-boron, nickel-tungsten-phosphorus, nickel-molybdenum-boron, nickel-tungsten-tin-phosphorus, and nickel-copper-phosphorus. The final selection is dependent upon the final application and the economics of achieving the results required.

Electroless composites and polyalloys have made unique contributions to various engineering applications. Extensive field testing is ongoing to gain experience for proper applications, inclusions and sizes, plus proper electroless bath operating parameters for these new forms of electroless plating.

WASTE TREATMENT

The electroless bath has limited life due to the formation of reaction byproducts. For example, in acid electroless nickel (hypophosphite-reduced) baths, the added accumulation or concentration of orthophosphite (HPO_3^{2-}) in the solution will eventually decrease the plating rate and deposit quality, requiring bath disposal. Also, the chelators and stabilizers make it difficult to reduce the electroless metal content by alkaline precipitation. Regulations regarding effluent discharge vary globally and with respect to local POTW limits. In the United States, electroless metal legal discharge limits of 1 ppm or below are common for nickel and copper effluents.

Conventional precipitation to form metal hydroxide or sulfide sludge through continuous or batch treatment involves a series of pH adjustment steps to convert dissolved metals into solids for dewatering and hazardous disposal. Emphasis must be placed on waste minimization as the first step in reducing waste treatment. Examples include ion exchange, reverse osmosis, and electrowinning or electrolytic recovery, which electroplates the spent bath into nickel or copper metal onto special cathodes helping to reduce the amount of sulfide or hydroxide hazardous sludge eventually created. The resultant plated metal produced can be reclaimed as scrap metal. Other waste minimization methods include using steel wool to plate out the electroless bath prior to further waste treatment.

IMMERSION PLATING

by Stanley Hirsch

Leeam Consultants Ltd., New Rochelle, N.Y.

and Charles Rosenstein

AMZA Ltd., Holon, Israel

Immersion (displacement) plating is the deposition of a metallic coating on a base metal from a solution that contains the coating metal. One metal is displaced by a metal ion that has a lower oxidation potential than the displaced metal ion. This differs from electroless plating because, in immersion plating, reducing agents are not required to reduce the metal ions to metal, as the base metal acts as a reducing agent. When a steel part is immersed in a copper sulfate solution, the following reaction occurs:

$$Fe + Cu^{+2} \rightarrow Cu + Fe^{+2}$$

The iron displaces the copper from its solution and the copper coats the steel part.

The thickness of deposits obtained by immersion plating is limited because deposition stops when the entire surface of the base metal is coated. Higher temperatures increase reaction rates of immersion baths and stirring is sometimes beneficial. Parts must be properly cleaned prior to immersion.

Immersion baths are usually inexpensive and have excellent coverage. They permit plating on difficult surfaces such as on the inside of tubing or in cases where there is difficulty in making electrical connections to isolated areas of the base metal. Immersion deposits are used for decorative purposes or as lubricants in drawing steel wire or shapes.

The accepted safety rules for handling acids, bases, cyanides, and other solutions should be followed when operating an immersion bath. Fume hoods should be used when a process involves the liberation of hazardous or annoying fumes.

Table I gives the ingredients and operating temperatures for a variety of immersion deposits on different substrates.

Table I. Immersion Plating Formulations

Type of Deposit	*Base Metal*	*Ingredients*		*Temperature (°F)*	*Comments*
Brass	Aluminum	Zinc oxide	112.5 g/L (15.0 oz/gal)	115	
		Sodium hydroxide	315.0 g/L (42.0 oz/gal)		
		Copper cyanide	13.1 g/L (1.75 oz/gal)		
		Sodium cyanide	22.5 g/L (3.0 oz/gal)		
		Basic lead carbonate	0.14 g/L (0.018 oz/gal)		
Bronze	Steel	Stannous sulfate	3.8 g/L (0.5 oz/gal)	Room	Liquor finish on wire.
		Copper sulfate	1.5 g/L (0.2 oz/gal)		
		Sulfuric acid	11.0 ml/L (1.4 fl oz/gal)		
Cadmium	Aluminum	Cadmium sulfate	3.8 g/L (0.5 oz/gal)	Room	
		Hydrofluoric acid, 70%	70.0 ml/L (9.0 fl oz/gal)		
	Copper alloys	Cadmium oxide	10.5 g/L (1.4 oz/gal)	105–160	
		Sodium cyanide	90.0 g/L (12.0 oz/gal)		
	Copper alloys and steel	Cadmium oxide	4.5 g/L (0.6 oz/gal)	255	
		Sodium hydroxide	540.0 g/L (72.0 oz/gal)		
Copper	Aluminum	Copper sulfate	99.8 g/L (13.3 oz/gal)	Room	Alkaline solution. If difficulty arises in plating certain aluminum alloys, try acidic formulation below.
		Ethylenediamine	99.8 g/L (13.3 oz/gal)		
	Aluminum	Copper sulfate	202.5 g/L (27.0 oz/gal)	Room	
		Hydrofluoric acid, 70%	7.0 ml/L (0.9 fl oz/gal)		
	Steel	Copper sulfate	15.0 g/L (2.0 oz/gal)	Room	
		Sulfuric acid	0.5 ml/L (0.06 fl oz/gal)		
	Zinc	Copper sulfate	30.0 g/L (4.0 oz/gal)	Room	
		Tartaric acid	52.5 g/L (7.0 oz/gal)		
		Ammonia	55.0 ml/L (7.0 fl oz/gal)		
Gold	Copper alloys	Potassium gold cyanide	2.3 g/L (0.3 tr oz/gal)	150–180	
		Potassium cyanide	12.0 g/L (1.6 oz/gal)		
	Copper alloys	Hydrogen tetrachloroaurate	1.0 g/L (0.1 tr oz/gal)	Room	Ethanol rinse.
		Ethanol	1000.0 ml/L (128.0 fl oz/gal)		

Table I. Immersion Plating Formulations *(cont.)*

Type of Deposit	*Base Metal*	*Ingredients*		*Temperature (°F)*	*Comments*
	Copper alloys and palladium	Potassium gold cyanide	5.0 g/L (0.6 tr oz/gal)	150–180	Thiourea may be used in place of urea.
		Ammonium citrate	20.0 g/L (2.7 oz/gal)		
		Urea	25.0 g/L (3.3 oz/gal)		
Lead	Copper alloys	Lead monoxide	3.8 g/L (0.5 oz/gal)	180–200	
		Sodium cyanide	26.3 g/L (3.5 oz/gal)		
		Sodium hydroxide	105.0 g/L (14.0 oz/gal)		
Nickel	Copper alloys	Nickel sulfate	60.0 g/L (8.0 oz/gal)	100–150	
		Ammonium nickel sulfate	60.0 g/L (8.0 oz/gal)		
		Sodium thiosulfate	120.0 g/L (16.0 oz/gal)		
	Steel	Nickel sulfate	15.0 g/L (2.0 oz/gal)	160	Adjust pH to 3.0–4.0 with sulfuric acid.
	Zinc	Nickel sulfate	60.0 g/L (8.0 oz/gal)	150	Adjust pH to 5.0 with sodium carbonate or sulfuric acid.
		Sodium chloride	30.0 g/L (4.0 oz/gal)		
Palladium	Copper alloys and nickel	Palladium (II) chloride	8.2 g/L (1.0 tr oz/gal)	Room	Seal the porous deposit by immersion in 33% by volume ammonia solution.
		Hydrochloric acid	250.0 ml/L (32.0 fl oz/gal)		
Platinum	Copper alloys, nickel, and gold	Chloroplatinic acid	12.3 g/L (1.5 tr oz/gal)	150	
		Hydrochloric acid	250.0 ml/L (32.0 fl oz/gal)		
Rhodium	Copper alloys	Rhodium (III) sulfate	4.8 g/L (0.6 tr oz/gal)	Room	
		Sulfuric acid	25.0 ml/L (3.2 fl oz/gal)		
Ruthenium	Copper alloys, gold, and palladium	Ruthenium nitrosyl chloride	11.5 g/L (0.6 tr oz/gal)	200	
		Hydrochloric acid	250.0 ml/L (32.0 fl oz/gal)		
Silver	Copper alloys	Silver cyanide	7.5 g/L (0.9 tr oz/gal)	Room	
		Sodium cyanide	15.0 g/L (2.0 oz/gal)		
	Copper alloys	Silver nitrate	7.5 g/L (0.9 tr oz/gal)	Room	Caution: Avoid skin contact, as silver nitrate discolors skin.
		Ammonia	100.0 ml/L (12.8 fl oz/gal)		
		Sodium thiosulfate	105.0 g/L (14.0 oz/gal)		
	Zinc	Silver cyanide	6.0 g/L (0.7 oz/gal)	Room	
		Potassium cyanide	3.8 g/L (0.5 oz/gal)		

Table I. Immersion Plating Formulations *(cont.)*

Type of Deposit	*Base Metal*	*Ingredients*		*Temperature (°F)*	*Comments*
Tin	Aluminum	Sodium stannate	45.0 g/L (6.0 oz/gal)	150–180	High sodium hydroxide causes blisters. Solution used for coating aluminum pistons.
	Copper alloys	Stannous chloride	18.8 g/L (2.5 oz/gal)	Room	
		Sodium cyanide	187.5 g/L (25.0 oz/gal)		
		Sodium hydroxide	22.5 g/L (3.0 oz/gal)		
	Copper alloys	Potassium stannate	45.0 g/L (6.0 oz/gal)	100–150	
		Potassium cyanide	105.0 g/L (14.0 oz/gal)		
		Potassium hydroxide	7.5 g/L (1.0 oz/gal)		
	Copper alloys	Stannous chloride	3.8 g/L (0.5 oz/gal)	80–120	
		Thiourea	49.5 g/L (6.6 oz/gal)		
		Sulfuric acid	12.0 ml/L (1.5 fl oz/gal)		
	Steel	Stannous sulfate	1.5 g/L (0.2 oz/gal)	180–Boling	Produces white finish on wire.
		Sulfuric acid	7.0 ml/L (0.9 fl oz/gal)		
	Zinc	Stannous chloride	127.5 g/L (17.0 oz/gal)	Room	
Zinc	Aluminum	Zinc oxide	90.0 g/L (12.0 oz/gal)	Room	
		Sodium hydroxide	450.0 g/L (60.0 oz/gal)		
	Steel	Zinc chloride	60.0 g/L (8 oz/gal)	Room	Place parts in zinc baskets or mix parts with small zinc pieces
		Ammonium chloride	30.0 g/L (4.0 oz/gal)		

SURFACE TREATMENTS

ELECTROPOLISHING

by Kenneth B. Hensel

Electro Polish Systems Inc., Milwaukee

The electropolishing system smoothens, polishes, deburrs, and cleans steel, stainless steel, copper alloys, and aluminum alloys in an electrolytic bath. The process selectively removes high points on metal surfaces, giving the surface a high luster.

HOW IT WORKS

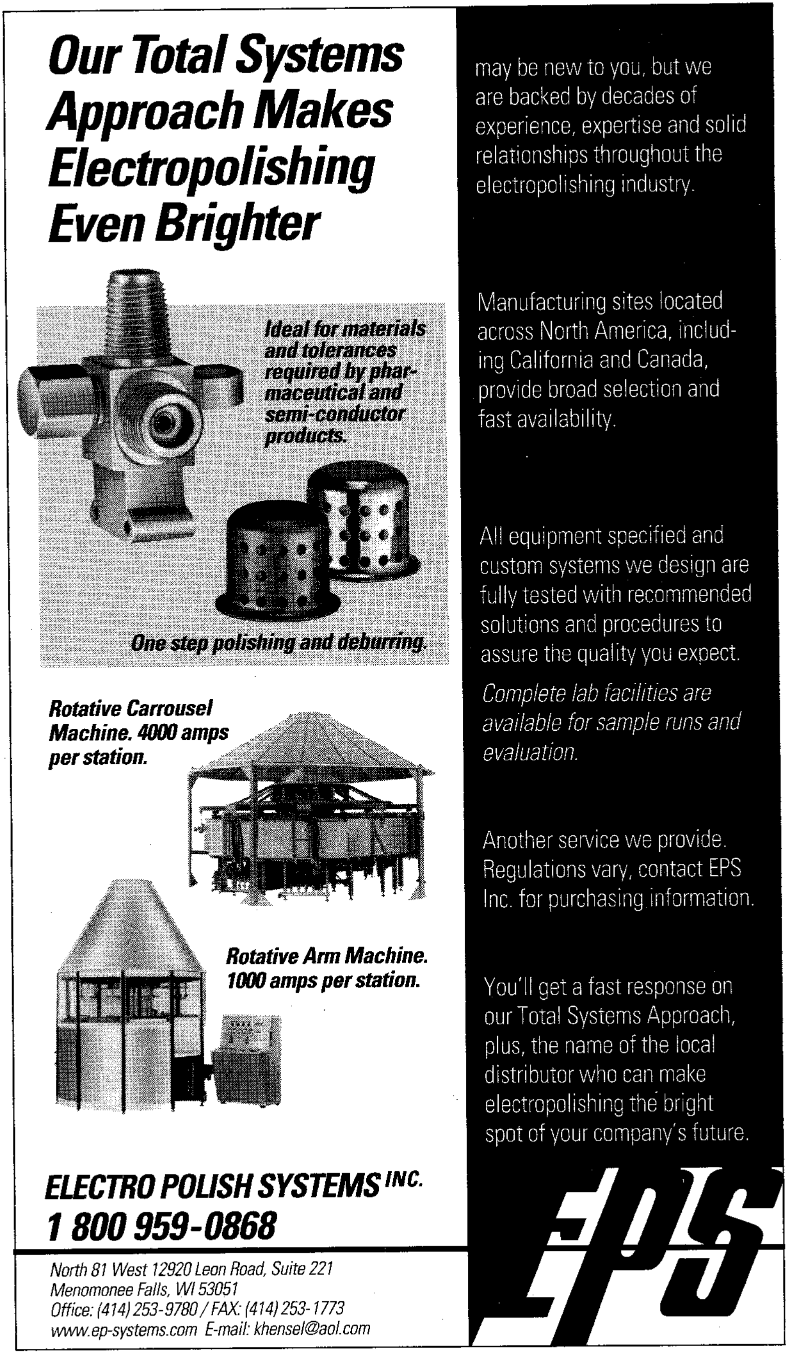
The metal part is immersed in a liquid media (electrolyte) and subjected to direct current. The metal part is made anodic (+) and a metal cathode (−), usually 316L stainless steel or copper, is used. The direct current then flows from the anode, which becomes polarized, allowing metal ions to diffuse through the film to the cathode, removing metal at a controlled rate. The amount of metal removed depends on the specific bath, temperature, current density, and the particular alloy being electropolished. Generally, on stainless steel, 0.0005 in. is removed in 1,500 amp-minutes per square foot. Current and time are two variables that can be controlled to reach the same surface finish. For example, 100 A/ft^2 electropolished for 5 min is 500 amp-minutes; 200 A/ft^2 for 2½ min is 500 amp-minutes. Both pieces of metal would have about the same surface profile. Current densities of 90 to 800 A/ft^2 are used in this process depending upon the part to be polished and other parameters. Electropolishing times vary from about 1–15 minutes.

ADVANTAGES

Conventional mechanical finishing systems tend to smear, bend, stress, and even fracture the crystalline metal surface to achieve smoothness or luster. Electropolishing offers the advantages of removing metal from the surface producing a unidirectional pattern that is both stress- and occlusion-free, microscopically smooth, and often highly reflective. Additionally, improved corrosion resistance and passivity are achieved on many ferrous and nonferrous alloys. The process micro- and macro-polishes the metal part. Micro-polishing accounts for the brightness and macro-polishing accounts for the smoothness of the metal part.

Deburring is accomplished quickly because of the higher current density on the burr, and because oxygen shields the valleys, enabling the constant exposure of the tip of the burr.

Because the metal part is bathed in oxygen, there is no hydrogen embrittlement to the part. In fact, electropolishing is like a stress-relieve anneal. It will remove hydrogen from the surface. This is important to parts placed under torque.



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Another benefit is that bacteria cannot successfully multiply on a surface devoid of hydrogen, therefore, electropolishing is ideal for medical, pharmaceutical, semiconductor, and food-processing equipment and parts. The combination of no directional lines due to mechanical finishing, plus a surface relatively devoid of hydrogen, results in a hygienically clean surface where no bacteria or dirt can multiply or accumulate.

SUMMARY OF UNIQUE QUALITIES AND BENEFITS

- Stress relief of surface
- Removes oxide
- Passivation of stainless steel, brass, and copper
- Superior corrosion resistance
- Hygienically clean surfaces
- Decarbonization of metals
- No hydrogen embrittlement
- No direction lines
- Low-resistance welding surface
- Reduces friction
- Both polishes and deburrs odd-shaped parts
- Radiuses or sharpens edges depending upon rack position
- Reduces annealing steps

SIMPLICITY OF THE SYSTEM

Practically speaking, three major process steps are necessary to electropolish most metal surfaces successfully:

1. Metal preparation and cleaning
2. Electropolish (electropolish drag-out rinse)
3. Posttreatment (rinse, 30% by volume of 42° Baumé nitric acid, rinse, deionized hot water rinse)

EQUIPMENT NEEDED FOR ELECTROPOLISHING

Electropolishing Tank

The electropolishing tank is generally constructed of 316L stainless steel, double welded inside and out. Stainless steel can withstand high temperatures, which are needed if too much water enters the electrolyte.

Polypropylene usually ¾ to 1-in. thick, is another tank choice. This tank can withstand temperatures of 180–190°F.

Power Supply

The direct current source is called a rectifier. The rectifier is generally matched to the size of the electropolish tank. If the tank is to be cooled by tap water through a plate coil, no more than 5.0 A/gal should be used, therefore, in a 500-gal tank, the capacity of the rectifier should not be more than 2,500 A. If 3,500 A are needed, then the tank size must be increased to compensate for the increased wattage going into the tank (amps × volts = watts).

Voltage is also determined by the number of amperes needed to electropolish the part. Generally, 600–3,000 A requires an 18-V DC output, and 3,500–10,000 requires a 24-V rectifier. Optimum running voltage is 9–13 V for stainless steel.

Aluminum requires a 30–40 V rectifier. Aluminum is run by voltage rather than amperage.

Racks

Electropolish racks for most metals are made of copper spines and crosspieces, which have been pressed in a thin skin of titanium. Copper, phosphor-bronze, or titanium clips are used and can be bolted on with titanium nuts and bolts. Some racks are made of copper and copper spines and are coated with PVC. These racks are generally for electropolishing of aluminum, copper, brass, and bronze, although titanium can be used here instead.

When building a rack, remember that 1 in.^{2} of copper carries 1,000 A; therefore, if you use two spines of 1 × ¼ in., this rack will carry 500 A.

When large volumes of parts are to be processed, a specially constructed barrel may be used, or a tray.

Agitation

An air line is usually placed diagonally on the bottom of the electropolishing tank to stir up the solution, preventing temperature stratification. Air is not used directly under the parts to be electropolished because "white wash" can occur.

Mechanical agitation is the optimum method for part agitation. This brings fresh solution to the surface of the part for faster electropolishing. Other methods of agitation are mixer, filter-pump, or separate pump.

Filtration is used on many electropolishing systems. The solution lasts longer and the tank does not have to be cleaned as often. In high-technology operations this may be a requirement.

Temperature

Most electropolishing solutions must be heated and cooled during the operating period. Heating is accomplished by using quartz or Teflon-coated stainless steel electric heaters with controls. If steam is used, Teflon coils are used. Lead is no longer used because it is toxic.

Cooling is accomplished with 316L stainless steel plate coils. Stainless steel cannot be used for steam heating as most baths contain sulfuric acid, which attacks stainless steel at the high-temperature surface of the plate coil. Tank construction of 316L stainless steel is all right because excessively high temperatures (above 250°F) are not present.

Chillers are used when the tank solution will have 10–15 A/gal from the rectifier.

Heat exchangers are used when input amperage is above 5 A/gal.

TYPICAL SOLUTIONS

There are organic electropolishing baths, inorganic baths, and organic/inorganic baths. Some typical formulas are shown below.

Aluminum

Because it is amphoteric in nature, aluminum can be electropolished in both acid and alkaline electrolytes. The brightening process involves low rate of attack, use of high-purity aluminum, and requires prefinishing.

Alzac Process: First Stage (Brightening)

Fluoboric acid, 2.5%
Temperature, 85°F
Voltage, 15–30 V
Current density, 10–20 A/ft^2

The polarized film is stripped in hot alkaline solution. Anodizing, as usual, in the sulfuric acid bath follows. Only superpurity alloys (99.95%) should be used.

Polishing and brightening are obtained in concentrated acid-type solutions that feature greater stock removal and greater smoothing.

Battelle

Sulfuric acid, 4.7%
Phosphoric acid, 75%
Chromic acid, 6.5%
Al^{3+} and Cr^{3+}, to 6%
Current density, 150 A/ft^2
Temperature, 175–180°F
Voltage, 10–15 V

Chromic acid decreases the etching rate, but changes from the hexavalent to trivalent form in use. Sulfuric acid drops the cell resistance or voltage, but increases the etching rate.

Copper and Alloys

R.W. Manuel

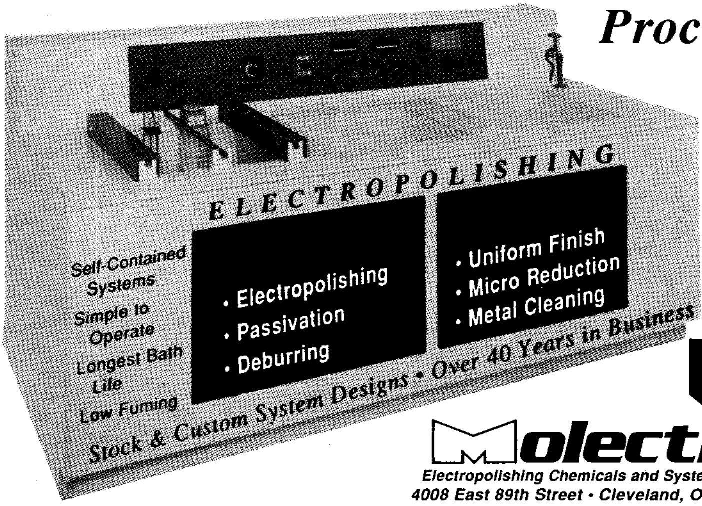
Water, 100 parts by wt
Chromic acid, 12.5 parts by wt
Sodium dichromate, 37.5 parts by wt
Acetic acid, 12.5 parts by wt
Sulfuric acid, 10.0 parts by wt
Current density, 250–1,000 A/ft^2
Temperature, 86°F

H.J. Wiesner

- Sodium tripolyphosphate, 14–16 oz/gal
- Boric acid, 4–5 oz/gal
- pH, 7–7.5 oz/gal
- Temperature, 125–135°F
- Current density minimum, 100 A/ft^2

S.B. Emery

Ammonium phosphate, 100 parts
Citric acid, 100 parts
Potassium phosphate, 25 parts
Water, 1,000 parts
Voltage, 6–25 V
Current density, 75–575 A/ft^2 (AC)



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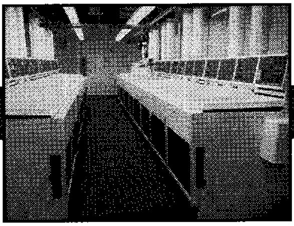

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ENEQUIST

Nickel and Alloys

Sulfuric acid, 60% minimum
Chromic acid, to saturation
Water, as required

Sulfuric acid, 60% minimum
Glycerin, 200 ml/L
Water, as required

Nickel sulfate, 240 g/L
Ammonium sulfate, 45 g/L
Potassium chloride, 35 g/L
Orthophosphoric acid, 15–70%
Sulfuric acid, 15–60%
Water, balance

Steel

Steel is more difficult to electropolish to the same degree of perfection as other metals, owing to variations. It has good potential in industrial applications, as well as for brightening and smoothing; however, results are not consistent because of great variations in composition and surface conditions from mills and/or heat treatment.

R. Delaplace and C. Bechard

Pyrophosphoric acid, 400 g
Ethyl alcohol to make 1 L
Temperature, 20°F
Current density, 300 A/ft^2

Cooling of the electrolyte is required, and water must be absent.

C. Faust

Sulfuric acid, 15%
Phosphoric acid, 63%
Chromic acid, 10%
Current density, 50–1,000 A/ft^2
Temperature, 125°F
This solution has a finite life.

Weisberg and Levin

Lactic acid, 33%
Phosphoric acid, 40%
Sulfuric acid, 15.5%
Current density, 100 A/ft^2
Temperature, 65–90°F
Polishing rate is quite low; 1–2 hr are required.

Hammond, Edgeworth, and Bowman

Phosphoric acid, 55–85%
Trialkali metal phosphate, 1–15%
Alkali metal sulfate, 0.5% minimum

Stainless Steel

Stainless steel is the most popular electropolished metal today. It retains its finish, and no aftertreatment is required.

H. Uhlig

Phosphoric acid and glycerine, 90%
Glycerin, >50%
Current density, >20 A/ft^2
Temperature, >200°F

J. Ostrofsky

Citric acid, 55%
Sulfuric acid, 15%
Current density minimum, 100% A/ft^2
Temperature, 200°F

This solution freezes below 130°F. Alcohol is recommended to reduce the freezing point.

C. Faust

Sulfuric acid, 15%
Phosphoric acid, 63%
Current density minimum, 50 A/ft^2
Temperature, 80–175°F

I. Clingan

Phosphoric acid, 56%
Sulfuric acid, 27%
Diethyleneglycolmonobutylether, 7%
Temperature, 125–165°F

Weisberg and Levin

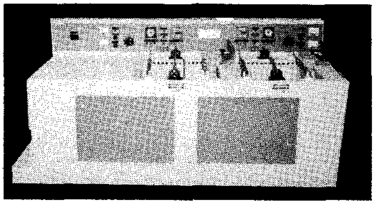
Lactic acid, 33%
Phosphoric acid, 40%
Sulfuric acid, 13.5%
Current density, 75–300 A/ft^2
Temperature, 160–200°F

C. Faust

Phosphoric acid, 56%
Chromic acid, 12%
Current density, 100–1,000 A/ft^2
Temperature, 80–175°F

J. Kreml

Sulfuric acid, 10–60%
Glycolic acid, 20–80%
Current density minimum, 150 A/ft^2
Temperature, 175–212°F



STRIPPING METALLIC COATINGS

by Charles Rosenstein

AMZA Ltd., Holon, Israel

and Stanley Hirsch

Leeam Consultants Ltd., New Rochelle, N.Y.

Metallic coatings are stripped when parts are rejected after plating because of one or more of the following defects:

1. lack of deposit uniformity;
2. discoloration;
3. roughness;
4. lack of adhesion;
5. poor coverage; or
6. insufficient thickness.

If the parts are valuable, reclamation via stripping and replating is feasible. Precious metals such as rhodium, gold, and silver are so valuable that even small quantities are worth reclaiming. In the printed circuit board industry, metallic resists such as tin or tin-lead are selectively stripped from contact tabs. The stripping should be done with as much care and planning as was required for the original plating process.

Acids used in stripper formulations must be sufficiently strong to remove the deposit being stripped, yet should not appreciably attack the base metal. The chemical activity of a specific acid can usually be suppressed by limiting the water content in a system. This is accomplished by either using concentrated acids such as sulfuric, acetic, or phosphoric, which contain little water, or by adding organics such as glycerine to the acids instead of water.

Chelating agents, which are specific for the metal being stripped, may be added to a stripping solution to prevent redeposition of the metal being stripped by immersion.

There are chemical and electrochemical methods for selectively stripping metallic coatings (see Table I). Immersion (chemical) strippers remove deposits by dissolution, whereas anodic (electrolytic) strippers plate out metal ions on cathodes. Immersion strippers are preferred for several reasons:

1. Complex-shaped parts are uniformly stripped.
2. Less equipment is required.
3. Operation is easy.
4. Racking is not required.
5. Electricity is not needed.
6. Less passivation occurs.

Proprietary strippers for all deposits can be purchased from many manufacturers.

Table I. Formulations for Stripping Metallic Coatings

Deposit Stripped	*Base Metal*	*Ingredients*		*Temperature (°F)*	*Volts*	*Cathode*	*Comments*
Brass	Nickel or steel	Sodium cyanide	90.0 g/L (12.0 oz/gal)	Room	6	Steel	Work is anodic. Use 2V for prolonged treatment, as high voltage may pit steel. For nickel: reactivate the nickel by cathodic treatment in hydrochloric acid prior to replating.
		Sodium hydroxide	15.0 g/L (2.0 oz/gal)				
	Steel	Ammonium persulfate	75.0 g/L (10.0 oz/gal)	70–85			
		Ammonia	375.0 ml/L (48.0 fl oz/gal)				
Bronze	Nickel or steel	Sodium cyanide	90.0 g/L (12.0 oz/gal)	Room	6	Steel	Work is anodic. Use 2V for prolonged treatment, as high voltage may pit steel. For nickel: reactivate the nickel by cathodic treatment in hydrochloric acid prior to replating.
		Sodium hydroxide	15.0 g/L (2.0 oz/gal)				
	Steel	Sulfuric acid	860.0 ml/L (110.0 fl oz/gal)	Room			
		Acetic acid	70.0 ml/L (9.0 fl oz/gal)				
		Nitric acid	70.0 ml/L (9.0 fl oz/gal)				
Cadmium	Brass, copper, or steel	Ammonium nitrate	120.0 g/L (16.0 oz/gal)	Room			
Chromate	Cadmium or zinc	Chromic acid	210.0 g/L (28.0 oz/gal)	190–212			Base metal is not attacked.
Chromium	Brass, copper, or nickel	Hydrochloric acid	125.0 ml/L (16.0 fl oz/gal)	125			
	Brass, copper, magnesium, or steel	Sodium hydroxide	52.5 g/L (7.0 oz/gal)	Room	6	Steel	Work is anodic.
		Sodium carbonate	67.5 g/L (9.0 oz/gal)				

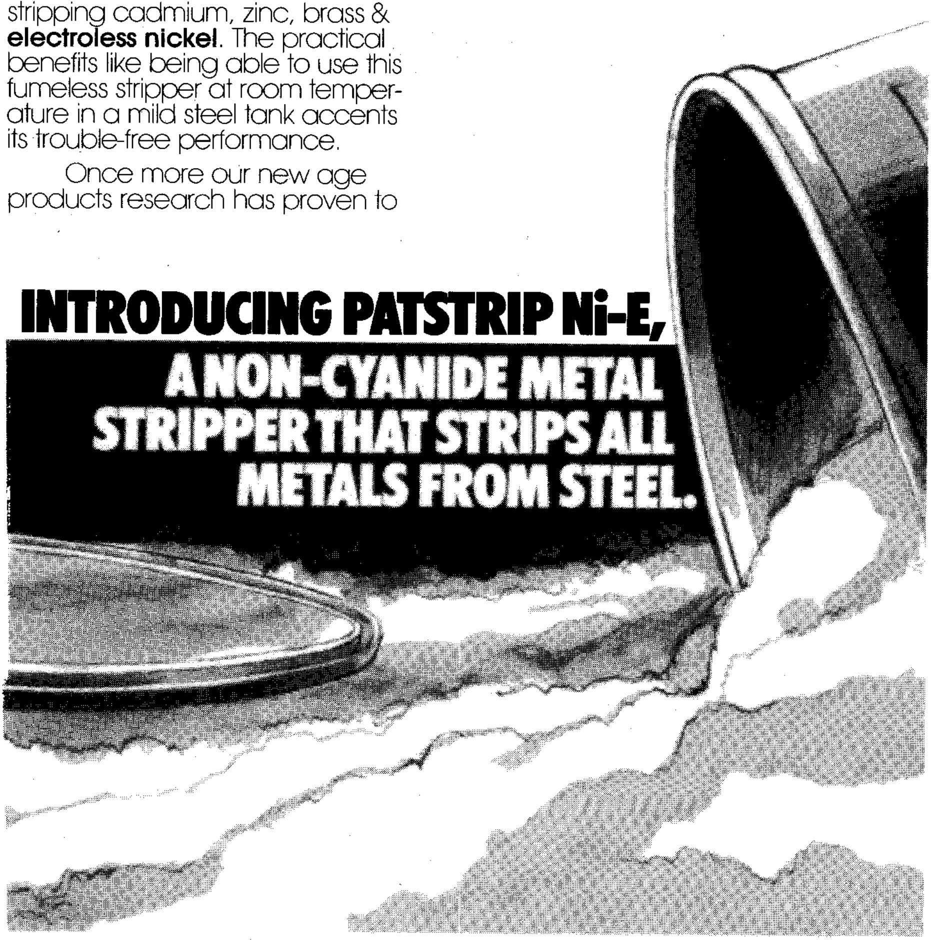

INTRODUCING PATSTRIP Ni-E,
A NON-CYANIDE METAL STRIPPER THAT STRIPS ALL METALS FROM STEEL.

Table I. Formulations for Stripping Metallic Coatings *(cont.)*

Deposit Stripped	*Base Metal*	*Ingredients*		*Temperature (°F)*	*Volts*	*Cathode*	*Comments*
Copper	Aluminum	Nitric acid	562.0 ml/L (72.0 fl oz/gal)	Room			
	Aluminum, brass, magnesium, or steel	Sodium sulfide	210.0 g/L (28.0 oz/gal)	185–205			Boil to dissolve sulfur. Immerse work, brush off loose copper sulfide, rinse, and dip in 10% sodium cyanide solution.
		Sulfur	15.0 g/L (2.0 oz/gal)				
	Nickel or steel	Sodium cyanide	90.0 g/L (12.0 oz/gal)	Room	6	Steel	Work is anodic. Use 2V for prolonged treatment, as high voltage may pit steel. For nickel: reactivate the nickel by cathodic treatment in hydrochloric acid prior to replating.
		Sodium hydroxide	15.0 g/L (2.0 oz/gal)				
	Steel	Chromic acid	480.0 g/L (64.0 oz/gal)	125			
		Sulfuric acid	31.0 ml/L (4.0 fl oz/gal)				
Gold	Copper or copper alloys	Potassium ferrocyanide	50.3 g/L (6.7 oz/gal)	120	6	Steel	Adjust pH to 9.0 with potassium dihydrogen phosphate. Work is anodic.
		Potassium cyanide	15.0 g/L (2.0 oz/gal)				
		Potassium carbonate	9.8 g/L (1.3 oz/gal)				
	Nickel or steel	Sodium cyanide	90.0 g/L (12.0 oz/gal)	Room	6	Steel	Work is anodic. Use 2V for prolonged treatment, as high voltage may pit steel. For nickel: reactivate the nickel by cathodic treatment in hydrochloric acid prior to replating.
		Sodium hydroxide	15.0 g/L (2.0 oz/gal)				
Lead or Tin-lead	Aluminum	Nitric acid, conc.		Room			
	Copper	Ammonium bifluoride	300.0 g/L (40.0 oz/gal)	70–90			Solution strips solder from circuit boards.
		Hydrogen peroxide	125.0 ml/L (16.0 fl oz/gal)				

Table I. Formulations for Stripping Metallic Coatings *(cont.)*

Deposit Stripped	*Base Metal*	*Ingredients*		*Temperature (˚F)*	*Volts*	*Cathode*	*Comments*
	Copper alloys or steel	Acetic acid	242.0 ml/L (31.0 fl oz/gal)	Room			Solution is less corrosive than fluoboric acid solution.
		Hydrogen peroxide	39.0 ml/L (5.0 fl oz/gal)				
	Copper alloys or steel	Fluoboric acid	125.0 ml/L (16.0 fl oz/gal)	Room			Solution does not have the acrid odor of an acetic acid solution.
		Hydrogen peroxide	39.0 ml/L (5.0 fl oz/gal)				
	Steel	Sodium hydroxide	99.8 g/L (13.3 oz/gal)	150			
		o-nitrobenzoic acid	50.3 g/L (6.7 oz/gal)				
	Steel	Sodium hydroxide	97.5 g/L (13.0 oz/gal)	180	6	Steel	Work is anodic.
		Sodium metasilicate	75.0 g/L (10.0 oz/gal)				
		Rochelle salts	52.5 g/L (7.0 oz/gal)				
Nickel	Aluminum, brass, copper, steel, or zinc die castings	Sulfuric acid	600.0 ml/L (77.7 fl oz/gal)	Room	6	Lead	Work is anodic. Stripping rate is increased by adding more water, but this also increases tendency to pit. 30 g/L (4.0 oz/gal) of copper sulfate or glycerine is added to reduce pitting of steel.
	Brass or copper	Sulfuric acid	100.0 ml/L (12.8 fl oz/gal)	150 maximum			
		m-nitrobenzene sulfonic acid	56.3 g/L (7.5 oz/gal)				
	Brass or copper	Sulfuric acid	950.0 ml/L (121.6 fl oz/gal)	120			Keep work dry before entering bath. Nitric acid additions reactivate the bath.
		Nitric acid	50.0 ml/L (6.4 fl oz/gal)				
	Magnesium	Ammonium bifluoride	158.3 g/L (21.1 oz/gal)	Room	6	Lead	Work is anodic.
		Sodium nitrate	19.5 g/L (2.6 oz/gal)				
	Steel	Sodium cyanide	75.0 g/L (10.0 oz/gal)	150 maximum			
		Sodium hydroxide	15.0 g/L (2.0 oz/gal)				
		m-nitrobenzene sulfonic acid	30.0 g/L (4.0 oz/gal)				

Table I. Formulations for Stripping Metallic Coatings *(cont.)*

Deposit Stripped	*Base Metal*	*Ingredients*		*Temperature (°F)*	*Volts*	*Cathode*	*Comments*
	Zinc die castings	Sulfuric acid	312.0 ml/L (40.0 fl oz/gal)	175 maximum	6	Lead	Work is anodic.
		Phosphoric acid	156.0 ml/L (20.0 fl oz/gal)				
		Chromic acid	67.5 g/L (9.0 oz/gal)				
Nickel-phosphorus (electroless nickel)	Brass, copper, or steel	Sodium hydroxide	60.0 g/L (8.0 oz/gal)	170			
		Ethylenediamine	120.0 g/L (16.0 oz/gal)				
		m-nitrobenzene sulfonic acid	60.0 g/L (8.0 oz/gal)				
Oxide-anodized coatings	Aluminum	Nitric acid	750.0 ml/L (96.0 fl oz/gal)	Room			
		Ammonium bifluoride	198.0 g/L (26.4 oz/gal)				
	Aluminum	Phosphoric acid	125.0 ml/L (16.0 fl oz/gal)	180–212			
		Chromic acid	120.0 g/L (16.0 oz/gal)				
	Magnesium	Chromic acid	180.0 g/L (24.0 oz/al)	120–160			
Black oxide	Steel	Hydrochloric acid, inhibited	500.0 ml/L (64.0 fl oz/gal)	Room			
Palladium	Brass, copper, silver, or steel	Sodium chloride	112.5 g/L (15.0 oz/gal)	Room	2–4		Work is anodic.
		Hydrochloric acid	4.0 ml/L (0.5 fl oz/gal)				
Phosphate Mn-type	Steel	Chromic acid	90.0 g/L (12.0 oz/gal)	165			
Mn-type and Zn-type	Steel	Sodium hydroxide	180.0 g/L (24.0 oz/gal)	160	6		Work is anodic.
		Sodium cyanide	90.0 g/L (12.0 oz/gal)				
		Sodium ethylene diamine tetra acetic acid (EDTA)	90.0 g/L (12.0 oz/gal)				

Table I. Formulations for Stripping Metallic Coatings *(cont.)*

Deposit Stripped	*Base Metal*	*Ingredients*		*Temperature (°F)*	*Volts*	*Cathode*	*Comments*
Platinum	Nickel or steel	Hydrochloric acid Nitric acid	250.0 ml/L (32.0 fl oz/gal) 500.0 ml/L (64.0 oz/gal)	Room			Solution is unstable and must be mixed fresh for each part stripped.
Rhodium	Nickel-plated brass	Sulfuric acid	500.0 ml/L (64.0 fl oz/gal)	90–100	7		Work is anodic. Nickel undercoat is dissolved and rhodium falls off.
	Nickel-plated brass	Hydrochloric acid	50.0 ml/L (6.4 fl oz/gal)	Room	6		Work is anodic. Agitate work to prevent pitting.
	Silver-plated copper alloys	Sulfuric acid Nitric acid	950.0 ml/L (121.6 fl oz/gal) 50.0 ml/L (6.4 fl oz/gal)	120			Keep work dry before entering bath. Nitric acid additions reactivate the bath.
Silver	Aluminum	Nitric acid, conc.		Room			
	Brass or copper	Sulfuric acid, conc. Sodium nitrate	 30.0 g/L (4.0 oz/gal)	70–120	3	Lead	Work is anodic.
	Brass, copper, or nickel-silver	Sulfuric acid Nitric acid	950.0 ml/L (121.6 fl oz/gal) 50.0 ml/L (6.4 fl oz/gal)	180			Keep work dry before entering bath. Nitric acid additions reactivate the bath. Use with care, as base metal may be attacked.
	Nickel or steel	Sodium cyanide Sodium hydroxide	90.0 g/L (12.0 oz/gal) 15.0 g/L (2.0 oz/gal)	Room	6	Steel	Work is anodic. Use 2V for prolonged treatment, as high voltage may pit steel. For nickel: reactivate the nickel by cathodic treatment in hydrochloric acid prior to replating.
Tin	Aluminum	Nitric acid, conc.		Room			
	Copper or copper alloys	Sodium hydroxide	120.0 g/L (16.0 oz/gal)	70–170	6	Steel	Work is anodic. Base metal may be attacked at high temperatures.
	Copper alloys	Fluoboric acid Hydrogen peroxide	125.0 ml/L (16.0 fl oz/gal) 39.0 ml/L (5.0 fl oz/gal)	Room			

Table I. Formulations for Stripping Metallic Coatings *(cont.)*

Deposit Stripped	*Base Metal*	*Ingredients*		*Temperature (°F)*	*Volts*	*Cathode*	*Comments*
	Steel	Sodium hydroxide	99.8 g/L (13.3 oz/gal)	100			
		Sodium thiosulfate	99.8 b/L (13.3 oz/gal)				
Tin-nickel	Copper alloys	Hydrochloric acid	250.0 ml/L (32.0 fl oz/gal)	Room	6	Carbon	Work is anodic.
	Steel	Sulfuric acid	600.0 ml/L (76.8 fl oz/gal)	Room	6	Lead	Work is anodic.
Zinc	Aluminum	Nitric acid, conc.		Room			
	Brass, copper, or steel	Sodium hydroxide	99.8 g/L (13.3 oz/gal)	Room	4	Steel	Work is anodic.
	Copper alloys or steel	Hydrochloric acid, inhibited	250.0 ml/L (32.0 fl oz/gal)	120			
	Copper alloys or steel	Ammonium nitrate	150.0 g/L (20.0 oz/gal)	Room			

ANTIQUING OF BRASS, COPPER, AND BRONZE

by Mark Ruhland

Birchwood Casey, Minneapolis

It's been said that "Beauty is in the eye of the beholder" and nowhere is this more true than in the antique hardware industry. Antique finishes have long been a popular option offered by manufacturers of decorative hardware of all types including lighting fixtures, locks, cabinet hardware, fasteners, and many other decorative items (see Fig. 1). Market demand for these finishes soared in the 1970s, leading to the development of efficient production-scale processing techniques. Since that time the demand has waxed and waned with the vagaries of the market. Regardless of the popular choices of the marketplace, there will always be a demand for high-quality antique-finished hardware.

This discussion will provide an overview of the various processes involved in the production of antique finishes. There are several different options available to the finisher at each step of the process and choices to be made, depending on relative efficiencies, operating cost, pollution implications, subsequent operations, etc. Consequently, the preferred process steps can vary widely from one plant to another. The process begins with the substrate.

SUBSTRATE METALS IN COMMON USE

There are three types of materials in common use.

Solid Brass, Bronze, or Copper

Available in several forms, these materials are commonly employed in outdoor applications or high-quality indoor applications. Since these alloys tend to form protective oxide films they have come to be the materials of choice for items such as outdoor lighting fixtures, locks, marine hardware, building trim, statuary items, certain fasteners, and other decorative items. This protective oxide film presents the finisher or designer with two options with respect to the finishing of the article: the piece can be given an "artificial" antique finish, which is preserved by outdoor-grade lacquers; or the article can be given an initial antique finish with only a temporary topcoat, which allows the surface to age naturally in service. This naturally developed oxide or patina is often more attractive than those artificially produced and is preferable for certain items such as builders' hardware, statuary, and some light fixtures.

There are several grades of these base metals employed in manufacturing the items described above. Solid grades of brass and copper sheet stock in varying alloys are used to manufacture light fixtures, fascia panels, and roofing for building construction, stamped or drawn fasteners, and other items that require malleability for ease of forming. Cast grades of brass and bronze are widely used for statuary, plaques, or high-quality hardware. Many of these items are further machined, polished, or belt sanded to form the final outer surface, which is then given an antique finish.

Steel Stampings, Spinnings, or Machined Items

Steel is often used in applications requiring higher load-bearing capacity than the pure copper alloys can offer such as fasteners or other structural members, which must be able to support some weight in service. In addition steel is usually less costly than solid copper, brass, or bronze and is often preferred because of these two factors. Unlike the copper alloys, steel

Fig. 1. Typical antique finishes.

does not form a protective oxide layer on exposure to weathering elements. Consequently, a steel article is usually electroplated with copper or brass in order to protect it from corrosion and present a viable brass or copper outer surface for subsequent antiquing operations.

Steel is commonly used to make structural hardware such as hinges, fasteners, casket hardware, and other functional items. Additionally, because of its relatively low cost, steel is used to make many indoor decorative items such as light fixtures and cabinet hardware. Many of these items are stamped out of sheet stock. Round items can often be formed in a metal spinning operation. This process begins with a flat disk of steel sheet, which is fastened to a shaped mandrel and rotated. The part is formed when a steel roller is pressed down onto the spinning surface, slowly forcing it to conform to the shape of the mandrel beneath it. Common items, such as lamp bases or bezels, are often formed this way, then brass or copper electroplated for antique finishing.

Zinc Diecastings

This third group is often used to make decorative items that have a detailed shape and have low load-bearing requirements. Many items have a design that is too detailed to make easily out of machined or stamped steel, or the value of the item is not high enough to justify the cost of cast bronze. For these lower-cost articles a zinc diecasting is the preferred base metal because it is easy to cast into very intricate shapes at relatively low cost, making it ideal for items such as cabinet hardware, light fixture components, and many other decorative articles. As with steel the zinc tends to corrode quite rapidly and must be electroplated with copper or brass for corrosion resistance and for antique finishing. Unlike steel, zinc diecastings can often have a porous surface, requiring the use of a copper strike in order to seal off this porosity prior to subsequent antiquing.

BEGINNING THE ANTIQUING PROCESS: CLEANING

Before chemical antiquing can begin on any substrate the surface must be free of oil, oxides, buffing compounds, mold-release compounds, soldering flux, fingerprints, or other foreign materials left over from the fabrication of the article. Once these materials are removed the surface is in a chemically active state and is ready for coloring, electroplating, or other operations. There are many cleaning options that could be considered. In selecting a metal-cleaning process, many factors must be taken into account including the identification of the substrate and the importance of the condition of the surface or structure to the ultimate use of the part; the identification of the soil to be removed; the environmental impact of the cleaning method; the cost of the operation; and the nature of the subsequent chemical operations to follow the cleaning step. Because of the variety of cleaning options available, each option deserves careful consideration.

In general one may rank the different cleaning options in the order of increasing degree of cleanliness as follows: abrasive blasting, cold solvent cleaning, vapor degreasing, emulsion soak cleaning, alkaline electrocleaning, alkaline soak cleaning followed by acid cleaning and finally ultrasonic cleaning. Each of these methods has its own advantages and disadvantages and is suited to particular types of soils. There is no universal cleaning method that works well on all types of soils. For example solid brass or copper items, which are soldered together, will have light oils and soldering flux on the surface, along with light tarnishing. These soils respond well to mild alkaline soak cleaners and may require mechanical agitation or scrubbing to remove all the flux. Cast bronze or brass items generally carry heavier oxides from the casting operation, but very little oil. Parts that can tolerate the surface roughening can be bead blasted with good success. Other cast parts, which ultimately require a bright, shiny finish, will be coated with buffing or polishing compounds that can be difficult to remove. In this case electrocleaning or ultrasonic cleaning works well. These methods provide a combination of alkaline emulsification of oils along with a mechanical action of the ultrasonic energy or current flow to help to mechanically lift these soils from the surface.

Stamped or spun steel parts usually have a layer of oil-based stamping lubricants on the surface. Because the steel can tolerate exposure to strongly caustic cleaners the preferred method is often a hot, caustic soak cleaner or electrocleaners, often followed by a milder alkaline cleaner to ensure free rinsing of the cleaning solutions. On the other hand, zinc diecastings are usually produced using a waxy mold release compound, which can be difficult to remove. In addition the zinc is a reactive metal that cannot tolerate a strongly caustic cleaner without being etched. Consequently, the best method here is a mold alkaline soak cleaner, electrocleaner, or, perhaps, ultrasonic cleaning at a moderate pH, which will not attack the zinc. Vapor degreasing can also be used with good success on machining or stamping oils or buffing compounds.

In general it is safe to say that cleaning is the most important part of the entire finishing process and is a prerequisite to uniform and adherent electroplating, antique finishing, and lacquer topcoats. Not only is cleaning the most important—it is also one of the least costly operations of the process line. Consequently, it pays to design the cleaning operation to do a thorough job on the metal surface and to perform all the recommended maintenance to the tanks. This practice represents an inexpensive insurance policy against poor quality finishes in subsequent steps.

As part of the cleaning operation, many parts benefit greatly from an acid cleaning to remove light oxides and to lower the pH of the surface. Here, several different materials can be used, including sulfuric, hydrochloric, or fluoboric acids or sulfuric acid salts, depending on the base metal and the desired activity of the acid.

TESTING FOR CLEANLINESS

The final evaluation of the effectiveness of a cleaning process should come from a performance test. The simplest and most widely used is the water-break test. It consists of processing the article or a standard test panel through the cleaning sequence in the normal manner, then dipping the part into clean water and observing how the water runs off the surface. A part that still carries residual oils will cause the water to bead up on the surface and form water breaks; whereas a part that is uniformly free of oil will allow the water to drain off uniformly with no water breaks. An oil-free surface will stay uniformly wet and the water will "sheet" off the surface rather than bead up.

Another method (useful on steel parts only) involves the use of an acid copper autoplating solution. Here, the cleaned surface is immersed in a dilute acid copper solution. A uniformly oil-free surface will allow metallic copper to be autoplated onto the surface in a uniform manner with no skips or bare spots. Any uncoated areas would indicate the presence of residual oils on the surface.

Once the part has been properly and completely cleaned of all foreign materials, it is ready to proceed to the next step in the antiquing process.

ELECTROPLATING

As mentioned earlier many parts do not require electroplating. Obviously any solid brass, bronze, or copper substrate would not necessarily be brass or copper plated as well. Once the surface is clean it would be ready for coloring in the appropriate solution. Other parts, however, such as steel or zinc diecast surfaces, do require an electroplated layer on the surface prior to being colored. Here, conventional plating techniques are used. The best quality plated finishes usually begin with a copper strike, followed by a generous brass or bronze deposit of approximately 0.0002 to 0.0003 in. thickness. The copper strike is an excellent way to seal off any porosity present in the base metal and make the surface more receptive to an adherent brass deposit of low porosity.

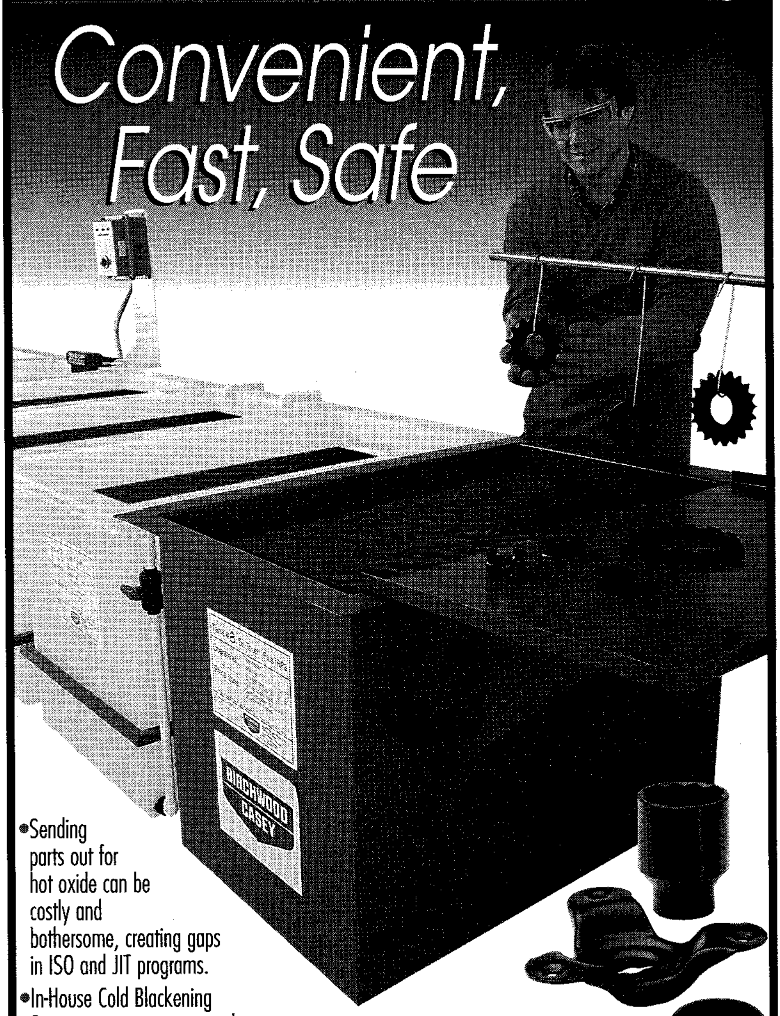
Most commercial brass plating baths contain cyanide. Noncyanide baths have enjoyed limited utilization because they often lack solution stability and produce deposits, which are darker in color and rougher than those of conventional cyanide baths. In addition, because they contain organic chelating agents, they can be more difficult to work with in waste treating the rinsewaters. A conventional cyanide bath forces the finisher to treat and decompose the cyanide residues in the rinsewaters, but the zinc and copper are often more easily precipitated. In this area the suppliers of the chemicals normally offer technical assistance in the correct operation and maintenance of the brass plating tanks. It is important to perform routine maintenance in order to keep these baths operating efficiently.

COLORING OF THE SURFACE

Once the surface has been plated with brass, it is ready to be colored by using one of several types of antiquing solutions available.

Sulfur and Arsenic-Based Solutions

The traditional way to color a brass surface is to oxidize it with one of these solutions. The sulfur-based method is often called "liver of sulfur" and utilizes a mixture of polysulfide salts to form a black or brown copper sulfide deposit on the surface. It works better on copper than it does on brass and has the inherent disadvantage of having a strong sulfur or "rotten egg" odor. In addition sulfur has several oxidation states and can form a variety of nonreactive polysulfide compounds, which greatly reduce its efficiency and tank life in a production operation. In actual practice the bath can be somewhat erratic in its oxidizing power from one



batch to the next and requires frequent dumping as it is not considered a replenishable product. It generally is considered unsuitable for production scale use.

Arsenic-based solutions form a black arsenic oxide on the surface and operate at room temperature; however, they carry a significant toxicity risk for the user and must be handled with extreme caution.

In addition to the two methods above there are other solutions that can be used on a small scale to color brass and bronze (see the article "Blackening and Antiquing" by Nathaniel Hall). These methods utilize a variety of chemicals to form colors on several metallic substrates and are designed for use by individual artisans rather than in production-scale antiquing operations.

Copper/Selenium Room-Temperature Oxidizers

Since selenium is directly related to sulfur on the Periodic Table of the Elements it undergoes many of the same reactions as sulfur. Consequently, these selenium-based solutions can be used to deposit a black or brown deposit on brass, bronze, or copper at room temperature and offer several advantages over the sulfur method. Most importantly, the selenium has fewer oxidation states than sulfur. This means that the solution is easier to control, with all the selenium going into reacting with the brass surface rather than forming nonreactive side compounds. The result is a bath that can be titrated and replenished and operated as a permanent bath in the line with no dumping necessary. This feature gives the finisher greater control over the operation of the bath in terms of reaction speed, the color of the finish produced, and the operating cost of the antiquing step.

The only caveat that must be observed is the fact that brass-plated parts will carry a cyanide residue on the surface, which must be neutralized prior to immersion in the antiquing solution. This is accomplished by momentary immersion in a weak (2–5%) sulfuric acid solution to neutralize and remove the cyanide from the surface. Skipping this step will result in low-level contamination of the antiquing solution by cyanide, which will tend to chelate or complex the copper content and reduce the effectiveness of the bath or disrupt the normal chemical balance.

In practice selenium-based oxidizers have proven to be the preferred way to blacken or brown a brass surface, due to their ease of operation, lack of fumes, dependable operation, and low cost. A variety of colors can be achieved, ranging from golden brown to medium and chocolate brown and black, depending on dilution level and immersion time in the solution. Since these baths are quite safe to work with it is usually easy for the operator to perform the necessary maintenance and operate the system without undue hazards.

Heated Caustic Oxidizers

These baths operate at 240°F and utilize caustic soda and sodium nitrate to oxidize the copper at the surface to a black cupric oxide. Since they react exclusively with the copper at the surface, a copper-rich surface favors the formation of a black deposit in the shortest time. Consequently, many brass parts are "dezincified" prior to blackening. This is done by immersing the parts in a warm caustic bath (180°F—not hot enough to blacken the surface) to dissolve most of the zinc out of the brass surface, leaving a copper-rich surface behind. At this point the part has a color, which is quite pink and is reactive enough to be blackened by the subsequent oxidizing bath.

These heated oxidizers can produce good quality black deposits and can be controlled by titration and/or boiling point. They do present an inherent danger to the operator because of the high operating temperature.

Black Nickel Coating

This process is an electrolytic blackening operation, which produces a black nickel sulfide coating on the surface. The finish is very hard and durable and, in many cases, produces a true black color, which the other methods cannot match. It is used most often as an extension of the brass plating operation. Since the parts are already racked for electrolytic deposition of the brass, they are ready for a second electrolytic operation—in this case blackening after thorough rinsing. The bath can be operated as a permanent plating bath in the line with periodic titration and replenishment and excellent tank life. Many experienced platers find that they can mix their own solution using commodity chemicals rather than purchase a preblended proprietary product. When operated in this way the operating costs can be quite low.

Black nickel works best on racked parts. Bulk or barrel handling methods work less well and usually result in more difficulty in achieving a uniform deposit, due to the continual interruption of electrical contact between the parts. As a result the black nickel finish is best suited for use on high value parts, which are rack plated.

Verde Green Patina

Also called "verdegris," this finish is a soft, pale-green color, similar to that seen on the aged copper roofs of older buildings. Actually, the authentic green patina formed on these roofs is a mixture of many different copper compounds including oxides, carbonates, sulfates, sulfides, and more. The composition is directly related to the purity of the air in the area. For example some copper roofs are more black than they are green due to a higher concentration of sulfur in the air from a coal-burning power plant in the vicinity. Others are greener owing to a concentration of nitrates in the air from automobile exhaust. Consequently, the color varies widely.

Artificial green patina solutions are, in simplest terms, mildly acidic corrosive copper solutions. They work by slowly tarnishing or corroding the surface of the brass or copper substrate and forming some of these same green or bluish colored copper compounds. These finishes can be quite attractive when properly applied. They have, however, two inherent disadvantages: the finish takes several hours to form and it is only loosely adherent to the metal surface. Consequently, the green patina solutions sold commercially tend to be workable only in small volume process lines where the finisher can afford to let the parts hang and corrode as they dry. And because the finish is loosely adherent it depends on the lacquer topcoat to provide the adhesion to the substrate to form a clean final finish.

HIGHLIGHTING AND BURNISHING THE FINISH

Once the parts have been colored or oxidized to the desired finish they are ready to be highlighted or burnished. This operation can take several forms depending on the final appearance requirements of the part. The essence of the operation is the removal of some or most of the colored finish to reveal portions of the underlying base metal in order to make it appear worn. In other words the colored finish is polished off the high points or highlights of the parts and allowed to remain in the recessed areas. The only way to accomplish this task is to mechanically remove the coating from these areas. There is no chemical treatment available to do this job. There are several proven methods that work well.

Hand Buffing

The buffing wheel is constructed of many disks on cotton fabric, sewn together to form a single buffing wheel about half an inch thick. These can be stacked together on a single spindle to form a buffing wheel up to 3 or 4 inches wide depending on what is needed to cover the part most effectively. Once the wheel is assembled it can be loaded with different compounds, ranging from abrasive to fine polishing compounds, depending on the type of contrast desired on the part's surface. For example some parts have designs, which have well-defined edges to the details or have sharp corners, etc. These parts generally would be highlighted with a fairly abrasive compound in order to clean off the colored coating completely from the highlights and allow the coating to remain almost entirely in the recesses. A dry nonmetallic abrasive flap wheel might also be used to achieve a sharp contrast.

On the other hand the part may have a rounder shape with softer curves and no clear-cut, sharp edges. This part may look better with a softer contrast burnishing than with sharp contrast abrasive buffing. If so the cotton wheel would be loaded with a less abrasive compound in order to achieve a softer shading or "feathering" of the colors on the part. Some parts go one step further requiring no actual removal of the antique finish but only a softening or burnishing of the coating of blend tones. This type of part might be buffed on a soft, brass wire wheel rather than a cotton wheel and a compound. This softer wire wheel would not really remove any coating, but merely smooth it out a bit or impart a soft directional grain to the surface. An alternative method might be to use a wet burnishing wheel—a brass wire wheel wetted with a slow dribble of water to soften the abrasive action.

It is easy to see that the hand-buffing operation is more art than science. Just as cleaning is important to the integrity of the deposit on the surface, buffing is critical to the final appearance of the finish and can even determine the market value of the piece. Since the decorative hardware business is all about appealing to the "the eye of the beholder," it is important to appeal to the eye of the buffer first.

Automated Buffing Machines

As in many other aspects of the finishing process higher production volumes also produce a need for automatic buffing capabilities in order to reduce labor costs and rely less heavily on the human factor in the buffing operation. Larger volume production lines often use very little hand buffing and have come to rely on automatic machines, which can be programmed to follow the shape of almost any part. These machines often take the form of a turntable surrounded by several buffing heads, each of which is oriented to buff just one aspect of the part as it passes by. Alternatively, some machines can index the part or rotate it so that a single buffing head does the entire job. The shape of the part will determine the type of machine that will be most suitable.

Tumbling and Vibratory Methods

Just as hand buffing is most often suitable for high value pieces, lower value parts can often be effectively highlighted in bulk. Parts, such as certain cabinet hardware, fasteners, or other small parts, would typically be brass plated or antiqued in bulk handling methods. If so it is desirable to burnish or highlight in bulk as well. To do this the parts can be burnished in a tumbler or in a vibratory mill.

A tumbler is a rotating drum, which rolls the parts against each other like a cement mixer. The parts can be burnished either wet or dry using a plastic or ceramic media with an abrasive or a polishing compound. Selecting the desired combination of these effects will produce a variety of different burnishing possibilities. The parts can generally be taken right off the process line, without drying, and loaded directly into the tumbler.

Vibratory finishers operate in a similar manner but use a vibrating bowl rather than a rotating drum. As mentioned the vibratory bowls can also be charged with different types of media and compounds to achieve the type of contrast desired. Both the tumbler and vibratory mill will produce a nondirectional pattern on the part surface and cannot really reproduce the effect achieved by a hand-buffing operation; however, they operate at much lower cost and can be preprogrammed to produce the identical result batch after batch. Consequently, they are less dependent on the human factor for consistent quality. For certain parts compromising on quality a bit in order to control the cost allows the manufacturer to sell the finished piece at the desired price point and still make a profit.

PROTECTIVE TOPCOATS

After coloring and highlighting are completed the part is ready to be topcoated to protect it from corrosion. Even though the parts may look completely finished the decorative antique finish is quite susceptible to corrosion or tarnish unless protected. The products most often used to accomplish this are clear lacquers. As in all the previous operations there can be many options open to the finisher, depending on the durability required of the final finish, operating cost, equipment cost, environmental concerns, etc. In actual practice there are a few options that provide the most benefits.

Air-Dry Lacquers

These products can be water-based or solvent-based and commonly utilize acrylic or urethane polymers to form a protective film. The acrylics are the lower cost option and can provide an effective topcoat for many parts used indoors only, such as light fixtures, wall sconces, etc., that do not see heavy wear. Generally, solvent-based lacquers are more protective than water-based products but also present a potential solvent fume problem in terms of discharge into the atmosphere.

Baking or Cross-Linkable Resins

These products are widely used on parts that require high wear resistance and/or outdoor exposure and include polyurethanes, epoxies, and nitrocellulose lacquers—all of which can cross link during drying to form a very dense and tenacious film. Very often they are cured in an oven at 250 to 350°F for 10 to 20 minutes to speed drying. These products are suitable for high-value parts or surfaces that must be exposed to outdoor weathering elements.

It is also possible to use lacquers containing corrosion inhibitors that specifically protect copper alloys. The most widely used is benzotriazole and its related compounds. These materials can be blended into many types of lacquers in small concentrations and provide an extra measure of corrosion resistance, making them particularly well suited for use on items such as marine hardware, building components, etc.

Clear Powder Coats

Relatively new on the scene these topcoats produce coating thicknesses of 2 to 4 mils and offer extremely high protection levels. They are applied like any other powder coat in a dry, electrostatic spray followed by 350°F oven bake. Powder coats are not suitable for all parts. They work best on parts that have an open shape with few or shallow recessed areas and can be susceptible to the Faraday Cage Effect. This is commonly seen with any electrostatic or electrolytic operation (including plating) and prevents deposition in deep recesses. Consequently, it is difficult to powder coat the inside surfaces of many parts.

Electrophoretic Liquid Lacquers

These products are not new but they are just now coming into popular use. They are liquid lacquers used as an electrophoretic immersion at the end of the plating line followed by an oven cure. Though not commonly used on parts that are highlighted after coloring they do find use as a clear sealant over a solid black finish such as a black nickel. In this setting the part is racked and taken through the plating operation then black nickel and electrophoretic lacquer.

Paste Wax and Oil Finishes

Some parts do not require a permanent antique finish but are designed to allow the surface to age naturally in service. For example brass hand rails, building fascia panels, elevator panels, and other parts can be initially sealed with a temporary protective film such as paste wax or oil. When installed they will be handled during normal use and constantly "burnished" by this contact. Over time they will develop a natural, soft patina that will ultimately be permanent because it is being constantly developed.

TYPICAL PROCESS CYCLES

Solid Copper or Brass (For example, a soldered light fixture assembly.)

1. Mild alkaline soak clean: 8–10 oz/gal mix; 150°F; 4–6 minute soak with air agitation.
2. Dragout rinse: nonflowing rinse to remove most of the cleaner residues.
3. Overflow rinse: treated by ion exchange.
4. Mild acid tarnish remover: 10% sulfuric acid; room temperature; 1–3 minutes.
5. Overflow rinse: treated by ion exchange.
6. Oxidize: blacken or brown in room-temperature oxidizing solution; 1–3 minutes.
7. Overflow rinse: treated by ion exchange.
8. Final rinse: deionize water to minimize water staining during drying.

Steel Stamping (For example, a rack-processed stamped lamp base.)

1. Heavy-duty alkaline soak clean: 10–12 oz/gal mix; 170–180°F; 4–6 minute soak.
2. Alkaline electroclean; 12 oz/gal of high caustic formula, 160°F; 6–12 V anodic current; 100–150 A/ft^2; 2–4 minutes.
3. Rinse: clean tap water; 20 seconds.
4. Rinse: clean tap water; 20 seconds.
5. Acid pickle: hydrochloric acid; 30–40% by volume; room temperature; 2 minutes.
6. Rinse: clean tap water; 20 seconds.
7. Rinse: clean tap water; 20 seconds.
8. Copper strike: 75–120°F; 15–20 A/ft^2; 2 minutes.
9. Brass plate: 90°F; 6–10 V; 15–20 A/ft^2; 15–30 minutes.
10. Rinse: clean tap water; 20 seconds.
11. Sour rinse (to neutralize cyanide); 2% sulfuric acid; room temperature; 30 seconds.
12. Rinse: clean tap water; 20 seconds.
13. Oxidize in black nickel or room temperature solution.
14. Rinse: clean tap water; 20 seconds.
15. Rinse: deionized water (to minimize staining during drying).
16. Warm dry: 130°F.
17. Highlight: cotton buff with abrasive compound.
18. Lacquer: nitrocellulose lacquer.
19. Oven cure: 250°F; 15–20 minutes.

Zinc Diecasting (For example, rack-processed cabinet hardware.)

1. Deburr: vibratory finishing machine using ceramic media and deburring compound.
2. Mild alkaline soak clean: 120°F; 5 minutes.
3. Mild electroclean: 120°F; 3 minutes.
4. Rinse: 20 seconds.
5. Rinse: 20 seconds.
6. Acid pickle: sulfuric acid salt; 8 oz/gal, 75°F; 2 minutes.
7. Rinse: 20 seconds.
8. Copper strike: 2 minutes; 75–120°F.

9. Brass plate: 30 minutes; 90°F.
10. Rinse: 20 seconds.
11. Dezincify: 180°F; 5 minutes.
12. Rinse: 20 seconds.
13. Blacken: hot caustic oxidizer; 240°F; 15 minutes.
14. Rinse: 20 seconds.
15. Deionized water rinse; 20 seconds.
16. Dry: warm air.
17. Highlight: automatic buffing machine.
18. Lacquer.
19. Bake cure.

WASTE TREATMENT

This area is of critical importance to the metal-finishing industry because a chemical process line cannot operate without proper treatment of waste products, as mandated by the Federal EPA and appropriate state or local agencies. Since these process lines utilize a variety of different chemical products it is impossible to offer a simple overview of the waste treatment picture. A few comments are in order, however, about the types of wastes generated in these lines and the waste treatment methods commonly employed to achieve compliance with the regulations.

Alkaline Cleaning Residues

These residues are primarily composed of nonhazardous alkaline salts such as sodium hydroxide, sodium carbonate, sodium phosphates, wetting agents, and other compounds, which are not specifically regulated. By virtue of their operating pH they tend to dissolve metals from the parts being processed—in most cases copper and zinc. Simple pH adjustment is very effective in precipitating much of the metal content and bringing the effluent into acceptable pH range of 5 to 9. Any remaining metal content can be precipitated with the help of specialized flocculants.

Acid Residues

Acid solutions quickly dissolve metals from the parts being processed and, like the alkaline chemicals, respond well to simple neutralization techniques to precipitate the metal content. Acid and alkaline rinsewaters are typically mixed together for treatment and help to neutralize each other.

Cyanide Residues

The rinses following the brass plating bath will contain cyanide, copper, and zinc. This rinsewater is typically subjected to a cyanide destruct process, which oxidizes and decomposes the cyanide to harmless chemicals and also precipitates the copper and zinc content. The metallic sludge is then collected on filters and disposed of as hazardous solid waste.

Solid Waste

The waste treatment methods above generate hazardous solid waste in the form of metal-bearing precipitate, which is commonly collected on a particle filter cartridge or plate filter element. This solid waste can be sent out to a licensed waste treater for proper stabilization and landfilling.

Dragout Rinses

These are often used as preliminary rinses following a heated process tank such as a heated cleaning tank or plating tank. Dragout rinses are perhaps the single most effective and least costly way to minimize chemicals in the drain. They are typically followed by a treated rinse, which is fed to ion exchange or other treatment.

For process solutions carrying only a moderate level of metals, a single dragout rinse is sufficient. A brass plating tank, on the other hand, will contain fairly high concentrations of cyanide, which is costly to treat. Consequently, it is common to see two or three dragout rinses used to minimize the level of cyanide sent to waste treatment.

Copper and Selenium-Bearing Effluent

Room-temperature oxidizers are perhaps the simplest to operate because they respond so well to treatment by ion exchange techniques. Some lines are set up with the rinsewaters going in two different directions, so to speak; the rinsewaters from the alkaline clean and acid tarnish removers tend to neutralize each other in the drain and are sent to a pH adjustment to complete the precipitation process; meanwhile, the rinsewaters following the copper/selenium-based oxidizers can be treated by ion exchange to purify the water and reuse it with none of this water entering the drain. Another option, in many cases, is to treat all the rinsewater in the line with ion exchange. Since all the rinses can contain metals none can be considered sewerable. But, since the total dissolved solids content of these rinses is usually quite low ion exchange is able to purify all the rinsewaters, in many lines, and return them to the rinse tanks to be reused over and over again.

In general ion exchange works well when the total dissolved solids content of the water is 1,000 ppm or less. For higher concentrations pH adjustment and neutralization techniques are more efficient. Most ion exchange systems are equipped with a conductivity light, which signals the operator that the resin tanks are saturated and ready for regeneration. The regeneration can be performed on site or the resin tanks can be shipped to a licensed waste treater for regeneration.

Responsible chemical suppliers offer advice on proper waste treatment techniques for their products. There is a great deal of additional information available elsewhere in this edition of the *Metal Finishing Guidebook* or in other industry publications.

In summary there are many different aspects to antique finishing, which take some time and experience to learn. As long as the decorative hardware industry is in existence, however, these finishes will be in demand and will evolve to meet the needs of the marketplace. The trend is toward safer processes, less polluting chemicals, and easier and shorter processes. As always cost is of prime concern. The industry is working to eliminate the hazardous and costly elements of traditional processes and replace them with materials and techniques that are more compatible with modern-day priorities.

BLACKENING AND ANTIQUING

by Nathaniel Hall

Consultant, Brooklyn, N.Y.

An almost unlimited variety of shades and colors may be applied to metals by heat treatment, chemical dips, and electrolytic processes. The results obtained will depend more on the skill of the operator than on the formula used and will vary with changes in the composition of the basis metal, so that different effects will be obtained on yellow brass than on rich low brass, for example.

The use of chemical dips is termed oxidizing, although the oldest method and the one that produces the widest range of brown to black shades produces a metal sulfide finish by the use of alkaline sulfide solutions. Originally, liver of sulfur was universally employed, this chemical being a crude mixture of potassium polysulfides and thiosulfate, also called potassium sulfuret. Modifications of these formulas called for the use of sodium, potassium, barium, and ammonium sulfides, which were claimed to produce different shades, but almost all sulfide colors are now produced from solutions of polysulfides, which are sold in concentrated liquid form under a number of trade names, usually called oxidizing liquid.

All sulfide films require wet or dry scratch brushing and must be protected by a good topcoat of clear lacquer. Contrast in color, obtained by "relieving," can be produced by scratch brushing with a slurry of fine pumice, by hand rubbing with pumice paste, by buffing and by the use of a "greaseless" polishing compound on a buff to remove the sulfide from highlights of the surface. Small articles may be colored in bulk, then relieved by tumbling with abrasive media, followed by ball burnishing if bright highlights are required. In any case, the sulfide solution employed should be fairly dilute because concentrated solutions result in a brittle film that may be nonadherent.

Although literally hundreds of formulas have appeared in the literature, the processes described in this section include the more common finishes that have commercial application.

COPPER AND BRASS

Black on Brass

Copper carbonate, 1 lb
Ammonia, 1 qt
Water, 2½ qt
Temperature, 175°F

The copper carbonate and the ammonia are thoroughly mixed before adding the water. An excess of copper must be present. The color, which is a blue-black, may be fixed by a subsequent dip in a 2½% solution of caustic soda.

Gray Black on Brass

Hydrochloric acid, 1 gal
White arsenic, 2 lb
Antimony trichloride, 1¼ m

This solution is used hot, and no water should be added.

Blue on Brass

Lead acetate, 2–4 oz
Sodium thiosulfate, 8 oz
Acetic acid, 4 oz
Water, 1 gal
Temperature, 180°F

This will produce a blue color on a nickel deposit and on polished high carbon steel as well. The color will change if not lacquered.

Antique Green on Brass

Nickel ammonium sulfate, 8 oz
Sodium thiosulfate, 8 oz
Water, 1 gal
Temperature, 160°F

Hardware Green on Brass

Ferric nitrate, 1 oz
Sodium thiosulfate, 6 oz
Water, 1 gal
Temperature, 160°F

Brown on Brass or Copper

Potassium chlorate, 5½ oz
Nickel sulfate, 2¾ oz
Copper sulfate, 24 oz
Water, 1 gal
Temperature, 195–212°F

Chocolate Brown on Brass

Potassium permanganate, 1 oz/gal
Copper sulfate, 8 oz/gal

Immerse 2–3 min at 200–210°F.

Flemish on Brass

This finish is produced by arsenic plating using the formula below. The arsenic deposit, which is a dark gray-black color, is removed from the highlights, exposing the brass base, and then lacquered:

White arsenic (As_2O_3), 16 oz/gal
Caustic soda, 16 oz/gal
Sodium cyanide, ½ oz/gal
Temperature, 70–110°F
Current density, 3–20 A/ft^2
Voltage, 2¼–4 V
Anodes, steel

The arsenic content of this solution is about 12 oz/gal, and the free caustic soda, as determined by the sulfo-orange method, is about 4.5 to 5.0 oz/gal.

Addition of ½ to 1 oz/gal copper cyanide, dissolved in a minimum amount of sodium cyanide, will result in a darker color. The deposit, in this case, is more easily relieved, making it more suitable for antique finishes. If a steel tank is used as the container, it may be made the anode.

Crystallized Brass or Bronze

Copper sulfate, 8 oz
Ammonium chloride, 4 oz
Water, 1 gal

Use either cold or warm. After a crystallized effect has been obtained, a dip in a sulfide solution will bring out the crystal effect distinctly.

Light Brown on Copper or Brass

Barium sulfide, ½ oz
Ammonium carbonate, ¼ oz
Water, 1 gal

The color is made more clear by wet scratch brushing and repeating the dipping.

Barbedienne Bronze

Potassium sulfide, ½ oz
Red ammonium sulfide, ¼ oz.
Yellow antimony sulfide, ¼ oz
Ammonia, ½ oz
Water, 1 gal

Wet scratch brush and repeat dipping operations.

Verde Antique

Copper nitrate, 4 oz
Ammonia chloride, 4 oz
Calcium chloride, 4 oz
Water, 1 gal

Acetic acid, ½ gal
Ammonium chloride, 20 oz
Sodium chloride, 7 oz
Cream of tartar, 7 oz
Copper acetate, 7 oz
Water, ½ gal

These two finishes are also known as patina and are stippled on brass or copper and allowed to dry on. Articles made of copper or copper plated are usually given a black base color in a sulfide solution, which results in a dark background. The use of sodium salts results in a yellowish color, whereas ammonium salts impart a bluish cast.

Stippling can be repeated, and when the antique green color appears, immersion in boiling water will produce several different color effects. Other effects are obtained by incorporating some dry colors, such as light and dark chrome green, burnt and raw sienna, burnt and raw umber, ivory drop white, drop black, or Indian red, some almost reproducing the colors of ancient bronzes. The surface should be lacquered or waxed. A pleasing semigloss appearance is produced after lacquering by brushing with paraffin, beeswax, or carnauba wax on a goat-hair brush, rotating at about 750 rpm.

Tiffany Green

Copper sulfate, 8 oz
Ammonium chloride, 4 oz
Sodium chloride, 4 oz
Zinc chloride, 1 oz
Acetic acid, 2 oz
Water, 1 gal

The addition of 1 oz of glycerin will prevent the green from drying too fast and produce a more even color. The articles are immersed in this solution and if the color is not uniform the immersions are repeated as often as desired, allowing the work to dry thoroughly between immersions.

English Bronze on Brass

This finish is also known as old English and English brass finish. Two solutions are required:

Solution 1

Liver of sulfur or any polysulfide, ½ oz
Water, 1 gal

Solution 2

Copper sulfate, 2 oz
Water, 1 gal

After cleaning thoroughly, the work is dipped in solution 1 and then into solution 2, without rinsing between dips. The articles are then rinsed in clean, cold water, and the dipping operations are repeated until the desired shade is obtained.

For an even finish the articles are scratch-brushed dry and dipped once again in solution 1 alone for light shades and in both solutions 1 and 2 for dark shades. They are then scratch-brushed dry and lacquered.

Black on Copper

Immerse at room temperature in a solution of ¼ oz/gal liver of sulfur or liquid polysulfide. Colors will progress through the spectrum of yellow to dark purple to black. The strength of the solution should be such that the black color forms in about 1 min. If it forms much more rapidly the copper sulfide film will be brittle and nonadherent, and the concentration should be reduced.

Statuary Bronze or Copper

The same procedure and solution are employed as above for black on copper; however, the articles are removed when they show a reddish-purple iridescence and then rinsed. Dry scratch brushing will then result in a chocolate brown color.

SILVER

The finish used on silver is generally a gunmetal shade, known as French gray. This is produced by coloring the articles black and then relieving with pumice and water or with greaseless compound. The dark color remains in the recesses, whereas the highlights are given a semigloss finish.

The black color may be produced with a weak solution of any polysulfide, such as red ammonium sulfide or liver of sulfur, used hot and preferably with the addition of ammonia, when a darker color is desired. A concentration of 1 to 2 oz/gal is satisfactory. This process gives an adherent finish, permitting shading from a deep grayish-black to a lighter color and finally to the silver base. It may be applied with a brush instead of by immersion if only a portion of the article is to be "oxidized," less silver being removed in this way.

Another solution that is often used is an acid solution of tellurium chloride. The solution is prepared by dissolving 1 oz tellurium dioxide in ½ pt hydrochloric acid and then diluting with water. This solution may be used for dipping but is more commonly employed with a brush for filling in designs, such as borders of holloware, thus avoiding reaction with areas that are to remain white. The solution is used hot, and when applied by brush, it is advisable to heat the article also.

Silver flatware, which is often cleaned electrolytically in service in contact with a piece of aluminum, magnesium, or zinc, cannot receive an antique finish with sulfide because the cleaning process results in the reduction of the silver sulfide to metallic silver. The tellurium dip or a black nickel electrodeposit is employed for this purpose. Arsenic will also produce an almost identical color but is not used both because of toxicity and its tendency to diffuse into the underlying silver so that the antique finish disappears after a time. A cheap imitation antique silver may be produced, however, by first nickel plating and then applying an arsenic deposit and relieving.

IRON AND STEEL

Black

The following two solutions can be used for blackening a wide range of low-carbon and low-alloy steels. The finishes are known as caustic black, and proprietary formulations are available from a number of suppliers, a list of which can be found in the Directory section:

Caustic soda, 8 lb
Sodium nitrate, 1½ oz
Sodium dichromate, 1½ oz
Water, 1 gal

Caustic soda, 80 oz/gal
Potassium nitrate, 30 oz/gal
Potassium nitrate, 20 oz/gal

Both solutions are used at the boiling point (approximately 295°F) and are maintained at the temperature by water or caustic additions.

STAINLESS STEEL

The following three formulas are used for stainless steel. Proprietary baths are also available as for blackening steel.

Sodium dichromate, 1 lb
Potassium dichromate, 1 lb
Temperature, 750–850°F

Clean and immerse in 10% oxalic acid solution. Rinse and dry. Wipe off smut and dip in 1% sodium sulfide solution.

Sulfuric acid, 180 parts
Water, 200 parts
Potassium dichromate, 50 parts
Temperature, 210°F

Blueing Steel

The following five baths will produce a blue color on steel:

Ferric chloride, 2 oz
Mercuric nitrate, 2 oz
Hydrochloric acid, 2 oz
Alcohol, 8 oz
Water, 8 oz
Room temperature

Parts are immersed for 20 min, removed, and allowed to stand in air for 12 hr. Repeat this again and then boil in water for 1 hr. Dry, scratch brush, and oil.

Sodium thiosulfate, 8 oz/gal
Lead acetate, 2 oz/gal

Use boiling.

White arsenic, 16 oz
Hydrochloric acid, 1 gal
Water, ½ gal

Use warm.

Mercuric chloride, 4 parts
Potassium chlorate, 3 parts
Alcohol, 8 parts
Water, 85 parts
Room temperature

Caustic soda, 5 oz/gal
White arsenic, 5 oz/gal
Sodium cyanide, 1 oz/gal

Make parts cathodic, using steel anodes, at 2 A/ft^2 for 2 to 4 min. The blue color produced should be rubbed and oiled.

Browning Steel (Gun Barrels)

The following method for browning steel gun parts will give the most durable finish:

Copper sulfate, 20 g/L
Mercuric chloride, 5 g/L
Ferric chloride, 30 g/L
Nitric acid, 150 g/L
Denatured alcohol, 700 ml/L

The procedure is as follows:

1. Dip in solution or brush or sponge on.
2. Place in a hot box for 30 min at 175°F.

3. Transfer to a humidity box. This may be a box into which live steam is introduced. When the temperature reaches about 150°F, shut off the steam and allow to stand in the box until a uniform film of red rust forms.
4. Immerse in boiling water until the red rust is converted to a black oxide.
5. Dry and scratch brush with a steel wire brush.
6. Repeat the previous operations three times.
7. Oil with an oxidizing oil, such as linseed.

COLORING TIN

Black

Arsenious oxide, 20 oz
Copper sulfate, 10 oz
Ammonium chloride, 2 oz
Muriatic acid, 1 gal

This is diluted 1:1 with water and used cold.

Nitric acid, 5% by volume
Copper sulfate, ⅓ oz/gal

This formula is used to produce an antique finish on pewter, which is immersed until the surface darkens.

Sodium phosphate, 100 g
Phosphoric acid, 20 ml
Water, 1 L
Temperature, 60–90°C

The parts are made anodic in this solution at a current density of 40 A/ft^2. This process gives a hard, easily polished black.

COLORING ZINC

Black

Ammonium molybdate, 4 oz/gal
Ammonia, 6 fl oz/gal

For deep blacks the solution should be heated. Rinse in cold and then hot water. Do not rub before the finish has dried and hardened.

Copper sulfate, 6 oz/gal
Potassium chloride, 6 oz/gal

Use cold.

Brown

Double nickel salts, ½ oz/gal
Copper sulfate, ½ oz/gal
Potassium chlorate, ½ oz/gal

Use at 140°F with an intermediate wet scratch brushing to even out the color. Waxing improves this color considerably.

COLORING CADMIUM

Brown

Potassium dichromate, 1 oz/gal
Nitric acid, ½ fl oz/gal
Temperature, 150°F
Time, 6–8 min

Scratch brush after the first brown color develops; then immerse parts again to obtain rich deep brown.

Potassium permanganate, 160 g/L
Cadmium nitrate, 60–250 g/L
Ferrous sulfate, 5–10 g/L
Temperature, 180–200°F

Maintain acid with nitric acid.

Black

Ammonium molybdate, 2 oz/gal
Potassium nitrate, 1 oz/gal
Boric acid, 1 oz/gal
Temperature, 150°F
Time, 5–10 sec

Copper sulfate, 2½ oz/gal
Potassium chlorate, 3 oz/gal
Sodium chloride, 3 oz/gal
Temperature, 200°F

Parts should be moved rapidly in the bath while the color develops through the reddish to the black stage.

COLORING ALUMINUM

Black

Ammonium molybdate, 2 oz/gal
Ammonium chloride, 4 oz/gal
Boric acid, 1 oz/gal
Potassium nitrate, 1 oz/gal
Temperature, 180°F

Potassium permanganate, 10 g/L
Nitric acid, 4 ml/L
Copper nitrate, 25 g/L
Temperature, 75°F
Time, 10 min

Blue

Ferric chloride, 0.6 oz/gal
Potassium ferricyanide, 0.6 oz/gal
Temperature, 150°F

ANODIZING OF ALUMINUM

by Charles A. Grubbs

Houghton Metal Finishing, Alpharetta, Ga.

An aluminum part, when made the anode in an electrolytic cell, forms an anodic oxide on the surface of the aluminum part. By utilizing this process, known as anodizing, the aluminum metal can be used in many applications for which it might not otherwise be suitable. The anodizing process forms an oxide film, which grows from the base metal as an integral part of the metal and when properly applied imparts to the aluminum a hard, corrosion- and abrasion-resistant coating with excellent wear properties. This porous coating may also be colored using a number of methods.

Many acidic solutions can be used for anodizing, but sulfuric acid solutions are by far the most common. Chromic, oxalic, and phosphoric acids are also used in certain applications.

The morphology of the oxide formed is controlled by the electrolyte and anodizing conditions used. If the oxide is not soluble in the electrolyte, it will grow only as long as the resistance of the oxide allows current to flow. The resultant oxide is very thin, nonporous, and nonconductive. This particular property of the anodic oxide is useful in the production of electrolytic capacitors using boric and/or tartaric acids.

If the anodic oxide is slightly soluble in the electrolyte, then porous oxides are formed. As the oxide grows under the influence of the applied DC current, it also dissolves, and pores develop. It is this property that allows us to color the oxide using organic dyes, pigment impregnation, or electrolytic deposition of various metals into the pores of the coating.

By balancing the conditions used in the anodizing process, one can produce oxides with almost any desired properties, from the thin oxides used in decorative applications to the extremely hard, wear-resistant oxides used in engineering applications (hardcoating).

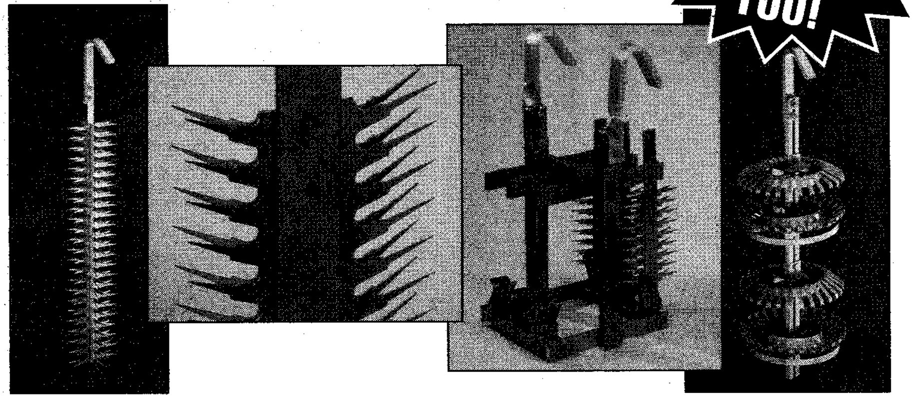
Colored anodized aluminum is used in a wide variety of applications ranging from giftware and novelties through automotive trim and bumper systems. Such demanding situations as exterior architectural applications or wear-resistant, abrasive conditions, such as landing gears on airplanes, are not beyond the scope of anodized aluminum. Semiprecious and precious metals can be duplicated using anodized aluminum. Gold, silver, copper, and brass imitations are regularly fabricated. New and interesting finishes are constantly being developed, which gain wide appeal across the spectrum of purchasers.

The utilization of electropolishing or chemical bright dipping in conjunction with a thin anodic oxide produces a finish whose appeal cannot be duplicated by other means. Matte finishes produced by etching the aluminum surface, affords the "pewter" look, which is oftentimes desired. Matte finishes are also the finish of choice of most architects.

EQUIPMENT

Tanks

A wide variety of materials can and have been used to build anodizing tanks. Lead-lined steel, stainless steel, lead lined wood, fiberglass-lined concrete, and plastic tanks have all been used in the past. A metallic tank can be used as the cathode, but adequate distance between the work and the tank must be maintained to prevent shorting. Some problems are experienced using metal tanks. For instance, the anode-to-cathode ratio is generally out of balance; also, since the entire tank is an electrical conductor, uneven current flow is possible leading to uneven oxide thickness formation. This uneven oxide formation causes wide color variations in organically dyed materials and is not generally recommended.



Generally, the use of inert materials in the construction (or lining) of the anodize tank is recommended. PVC, polypropylene, or fiberglass are good inert materials for this application.

Cathodes

Cathodes can be aluminum, lead, carbon, or stainless steel. Almost all new installations are using aluminum cathodes because of their ability to reduce the energy requirements of the process. Because of the better conductivity of aluminum, the anode-to-cathode ratio becomes extremely important. It has been found that an anode-to-cathode ratio of approximately 3:1 is best for most applications. Cathode placement is also of vital importance. It is recommended that the cathodes be no longer (deeper) than the work being anodized. Placement of the cathodes along the tank sides should be such that they extend no further than the normal work length. For example most 30-ft long tanks can only handle 28-ft lengths; therefore, the cathodes should be positioned at least 1 ft from either end of the tank to keep the work material from "seeing" too much cathode and anodizing to a thicker oxide on the ends. The depth of the cathodes in the tank should not exceed the normal depth of the work being processed. If the cathodes extend deeper into the tank than the parts being anodized, there will be excessive oxide growth on the parts in the lower portion of the anodizing tank. This will result in color differences in the oxide and subsequently colored parts.

The correct alloy and temper for aluminum cathodes is vital, 6063 or 6101 alloys in the T-6 or T-5 condition are best. The overaged T-52 temper *should never be used!* Cathode material should be welded to an aluminum header bar using 5356 alloy welding wire. Bolted joints are not recommended due to the possibility of "hot joints."

Employment of aluminum cathodes has done much to improve the overall quality of anodized finishes in all areas of application.

Temperature Control

This is one of the most important factors influencing the properties of the anodic oxide and must be closely controlled to produce consistent quality. The temperature should be held to plus or minus 2°F. Most installations have some means of temperature control, since large amounts of heat are generated in the anodizing process.

Lead cooling coils have been used in the past, but newer plants use external heat exchangers. The external heat exchanger has been found to be more efficient in cooling the solution while offering additional agitation. Again, as mentioned above, the presence of other metals in the tank, in conjunction with the aluminum cathodes, can cause undo electrical problems.

One of the added benefits of using a heat exchanger is agitation. Proper placement of the intake and outlet piping can insure good agitation as well as minimization of temperature variations within the tank. This type of acid movement assures one of better anodizing.

Recently, the use of acid "spargers" in the bottom of the anodize tank has become popular. These spargers replace the more common air spargers now being used and give much better acid circulation and temperature control.

Agitation

To prevent localized high temperatures, some form of agitation is required in the bath. Low-pressure air, provided it is clean and oil-free, is often used. Mechanical agitation and pumping of the electrolyte through external heat exchangers are also used. Generally, compressed air is not recommended due to the presence of oils in the lines. Multiple filters in the air lines when using compressed air have not proven to be completely effective in keeping oil out of the anodize tank.

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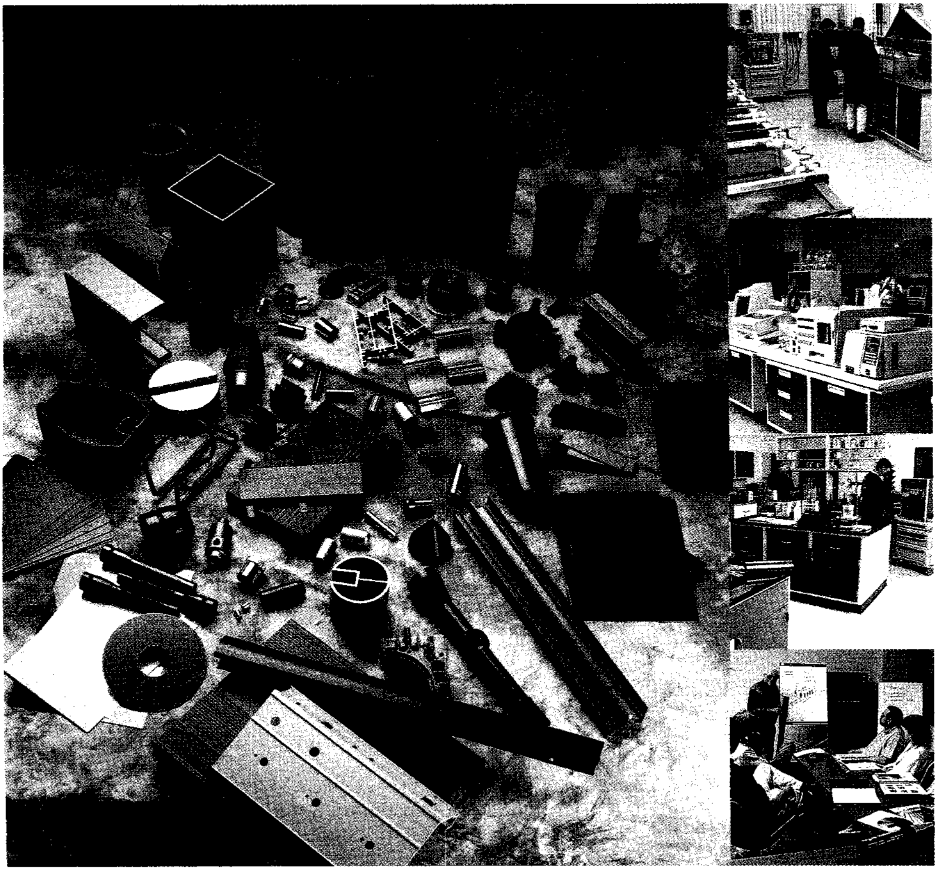

Leadership for Coloring and Finishing Anodized Aluminum

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A leader is **tested** — superior quality and perfor- nance are critical benchmarks in setting the standard. Ve've earned the recognition of anodizers for a broad pectrum of colorants and processing chemicals that meet he most stringent working and finishing demands.

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In the arena of coloring and finishing chemicals, **Clariant** is your trusted partner with a tested and proven record. We are dedicated to helping you develop the most efficient and effective processes for producing products that meet your customers' most demanding requirements.

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Racks

The two most common rack materials are aluminum and titanium. If aluminum is used, it should be of the same alloy as the work, or at least not be an alloy that contains copper (2xxx series). Alloys 6063 and 6061 are excellent rack materials. It must be remembered that aluminum racks will anodize along with the work and must be stripped before being used again. Titanium racks are more expensive, initially, but do not require stripping and are generally not attacked by the baths used in the anodizing process. Only commercially pure titanium can be used as rack material.

Titanium racks are not suitable for low temperature anodizing (hardcoating) where high voltages are required. The lower conductivity of the metal causes heating of the racks and eventual burning of the aluminum parts being anodized.

Power Equipment

For normal (Type II) sulfuric acid anodizing (68–72°F), a DC-power source capable of producing up to 35 V and 10 to 24 A/ft^2 should be suitable.

Some processes such as phosphoric acid, oxalic acid, hard coating, or integral color may require voltages as high as 150 V.

Power supplies come with a variety of options. Such things as constant current control, constant voltage control, adjustable ramping, end-of-cycle timers/signals/shut-offs, and a variety of other options make the anodizing process easier and more controllable.

Power supplies for hardcoat anodizing require more stringent capabilities. Those used for Type III low temperature anodizing (28–32°F) will require voltages approaching 90 V and amperages equivalent to 48 A/ft^2. Power supplies used for "room temperature" hardcoating (50–65°F) will require only 36 V and sufficient current to reach 36 to 46 A/ft^2.

SURFACE PREPARATION

The type of surface preparation prior to anodizing gives the metal finisher a choice of effects. By combining mechanical techniques, such as scratch brushing or sandblasting with buffing and bright dipping, interesting effects can be achieved. Sandblasting and shot peening have also been used to give interesting surface treatments.

The beauty of dyed anodized aluminum can be further enhanced by color buffing the work after it is sealed and dried, using a lime-type composition, preferably containing some wax. In addition to actually polishing the coating, this step removes any traces of the sealing smut.

Irregular shaped parts, castings, etc. are best finished by brushing with a Tampico brush or by tumbling with sawdust or other suitable media.

PRETREATMENT

Cleaning

Proper and thorough cleaning of the aluminum surface prior to anodizing is one of the most important steps in the finishing process. Improperly cleaned material accounts for more reruns and rejected parts than any other single factor.

It is essential that all machining oils, greases, body oils, and other surface contaminants be removed prior to the continuation of the anodizing sequence. Both alkaline- and acid-based proprietary cleaners are available that will do an adequate job. If the oils or greases are specific in nature, some cleaners may need to be "customized" for adequate results.

What is clean? Generally, we speak of a part being clean if it exhibits a "water-break-free" surface. This means that if the water rinses off of the metal surface in a continuous sheet,

the work is considered to be clean. If, on the other hand, the water "beads" up or forms water breaks, the part still has foreign matter on the surface and continued cleaning is necessary. Once the part has been determined to be clean, subsequent finishing steps can proceed.

Etching

Etching is the removal of some of the aluminum surface from a part using chemical solutions. There are a number of reasons for etching aluminum:

1. To impart a matte finish to the material (lower the specularity or gloss).
2. To remove surface contaminants.
3. To hide surface imperfections (scratches, die lines, etc.)
4. To produce an overall uniform finish.

Chemical etching is accomplished using both alkaline and acid solutions. The most frequently used etch media is sodium hydroxide. Time, temperature, concentration, and contaminant level will affect the type of finish possible in an etch bath. Many proprietary solutions are available from the chemical suppliers. Close attention to the technical information included with the chemicals is important.

Rinsing

Probably one of the most abused steps in the finishing of aluminum is rinsing. Most anodizers practice some form of "water management," usually to the detriment of the other process tanks. Improper rinsing causes poor surface finish due to cross reactions of chemicals left on the surface from previous processing tanks reacting with the chemicals in further processing tanks. Cross contamination of expensive solutions is another fallacy of "water management." Cascading rinses, spray rings, or just cleaner rinse tanks with adequate overflow will go a long way in reducing poor finish and cross contamination.

Deoxidizing/Desmutting

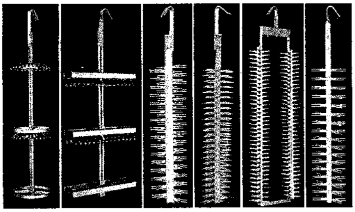
After etching, a "smut" of residual metallic alloying materials is left on the aluminum surface. This must be removed before further processing. The use of deoxidizer/desmutters will accomplish this, leaving the treated surface clean for subsequent finishing steps.

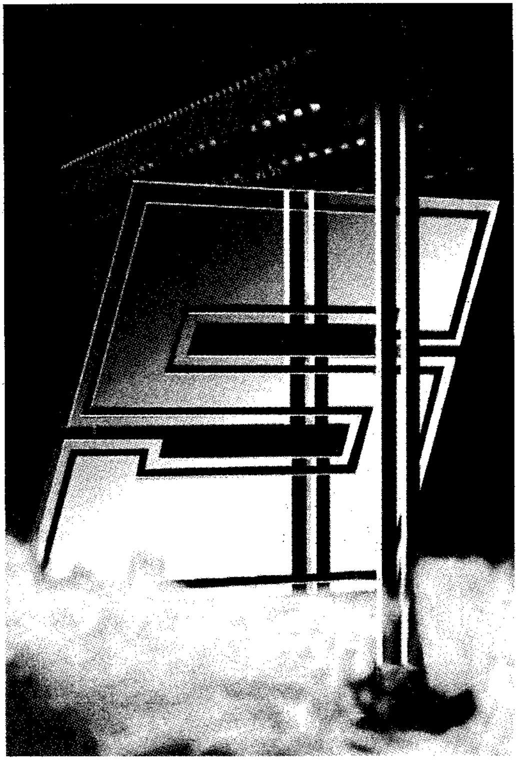
Many alloys, during their heat treatment steps, will form heat treat oxides. If these oxides are not removed prior to etching or bright dipping, a differential etch pattern can develop, which will cause rejection of the parts. In this instance a deoxidizer must be used. The deoxidizer is designed to remove oxides, but is also extremely good at removing smut. A desmutter, on the other hand, will not remove oxides. It is apparent that a deoxidizer would be the preferred solution to have in an aluminum finishing line. *Remember, a deoxidizer will desmut but a desmutter will not deoxidize.*

Bright Dipping and Electrobrightening

A chemical or electrobrightening treatment is required where an extremely high luster is to be obtained on the aluminum surface. The electrobrightening or electropolishing treatment is particularly applicable to the super-purity aluminum now used extensively in the jewelry and optical field. Proprietary chemicals for these treatments are available from a number of suppliers. Chemical brightening is most commonly used for most applications because of it's ease of operation. A number of companies offer proprietary solutions, which will give you the bright finish you desire. Specifics on the makeup and use of these solutions is available from the chemical suppliers.

For quality anodizing racks, *our* name keeps surfacing.





Titanium racks for anodizing and electropolishing are available from a lot of places, for use in your job shop, captive operation or the new line you're planning.

But while many racks are fabricated, only a few are really designed. Fact is, a poorly designed rack costs you more in lost production and rejects than it's worth.

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ANODIZING

Properties of the Oxide Film

The anodizing process conditions have a great influence on the properties of the oxide formed. The use of low temperatures and acid concentration will yield less porous, harder films (hardcoating). Higher temperatures, acid contents, and longer times will produce softer, more porous, and even powdery coatings. It must be remembered that changing one parameter will change the others, since they are all interrelated.

It should also be pointed out that the alloy being processed may significantly alter the relationship between the voltage and current density, often leading to poor quality coatings. This is particularly true when finishing assembled components, which may contain more than one alloy.

Factors Influencing Shade

In order to obtain reproducible results from batch to batch, a large number of variables must be kept under close control. First to be considered are those that affect the nature of the oxide.

Alloy

The particular aluminum alloy being used has a pronounced effect on shade, especially with certain dyes. The brightest and clearest anodic oxides are produced on the purest form of aluminum, the oxides becoming duller as the amount of alloying constituents are increased. Super-purity aluminum (99.99% Al) and its alloys with small amounts of magnesium produce an extremely bright oxide, which does not become cloudy upon being anodized for extended periods.

Alloys containing copper, such as 2011, 2017, 2024, and 2219, although forming a thinner and less durable oxide than the purer forms, produce a heavier and duller shade. Magnesium in excess of 2% has a similar effect although not as pronounced. The presence of silicon imparts a gray color to the coating; alloys containing more than 5% silicon are not recommended for use with bright colors. Iron in the alloy can lead to very cloudy or "foggy" oxides.

The majority of casting alloys contain appreciable amounts of silicon, ranging as high as 13%, and present difficulty in anodizing. Use of a mixed acid dip (normally containing hydrofluoric and nitric acids) prior to anodizing is of value when high-silicon alloys are encountered.

Since the various alloys produce different shades when anodized identically, the designer of an assembled part must use the same alloy throughout if the shades of the individual components are to match.

Anodizing Conditions

Other variables affecting the nature of the oxide i.e., its thickness, hardness, and porosity) are the acid concentration and temperature of the anodizing bath, the current density (or the applied voltage, which actually controls the current density), and the time of anodizing. These factors must be rigidly controlled in order to achieve consistent results.

The "standard" sulfuric acid anodizing bath (Type II) produces the best oxides for coloring. The standard anodizing solution consists of:

Sulfuric acid, 180–200 g/L
Aluminum, 4–12 g/L
Temperature, 68–72°F

As the anodizing temperature is increased, the oxide becomes more porous and improves in its ability to absorb color; however, it also loses its hardness and its luster, due to the dissolution action of the acid on the oxide surface. As the pore size increases, sealing becomes more difficult and a greater amount of color is bled (leached) out into the sealing bath. The ideal anodizing temperature, except where a special effect is desired, is 70°F.

Oxides produced by anodizing in chromic acid solutions may also be dyed. The opaque nature of the oxide film produced in this manner has a dulling effect upon the appearance of the dyed work. Consequently, some dyes, notably the reds, which produce pleasing shades on sulfuric acid anodized metal, are unsuitable for use with a chromic acid coating. Fade resistance of this type of dyed oxide is extremely poor, possibly because the oxide is not thick enough to contain the amount of dye needed for good lightfastness. The best chromic acid coatings for dyeing are produced with a 6 to 10% by weight solution operated at 120°F. A potential of 40 to 60 V is used, depending upon alloy, copper- and silicon-bearing materials requiring the lower voltage. The usual time is from 40 to 60 minutes.

DECORATIVE ANODIZING

Decorative anodic oxides are used in a great many applications, from lighting reflectors to automotive trim. The thickness of the oxide might range from 0.1 to 0.5 mil (2.5 to 12 microns). As mentioned above the most common electrolyte is sulfuric acid and typical conditions are listed below. Parts that are to be given bright specular finishes are usually produced from special alloys formulated for their bright finishing capabilities.

Typical decorative anodizing conditions are:

Sulfuric acid, 165–180 g/L
Temperature, 60–80°F
Current density, 10–15 A/ft^2
Voltage, depends on current density, temperature, and electrolyte
Time, 12–30 minutes depending on film thickness desired. Longer times produce thicker coatings.

ARCHITECTURAL ANODIZING

The conditions used in architectural anodizing are not much different than those used for decorative applications, except the anodizing time is usually longer and the current density may be slightly higher. In general the thickness of the oxide will be greater than for decorative coatings, and this relates to the treatment time.

Interior

For interior applications the coating will be probably 0.4 mil thick (10 microns). This means an anodizing time of about 20 minutes at 15 A/ft^2.

Exterior

For exterior uses the coating will be a minimum of 0.7 mil thick (18 microns) and this means an anodizing time of about 39 minutes at 15 A/ft^2.

INTEGRAL COLOR ANODIZING

This process, used mainly for architectural applications, requires the use of specially formulated electrolytes, usually containing organic sulfo acids with low contents of sulfuric acid and aluminum content, to produce a series of bronze to black shades. The color produced is dependent upon the time of treatment and the final voltage used. Specially formulated alloys are also required. Large amounts of heat are generated in the process due to the high current densities employed (up to 45 A/ft^2), so efficient heat exchange equipment is needed to keep the bath cool.

HARDCOATING

Hardcoating (Type III) is a name used to describe a special form of anodizing. The process, which usually employs higher acid concentrations, lower temperatures, and higher voltages and current densities is sometimes referred to as an "engineering hardcoat." This is due to the fact that hardcoating imparts a very hard, dense, abrasion-resistant oxide on the surface of the aluminum. A dense oxide is formed due to the cooling effect of the cold electrolyte (usually 30–40°F). At these temperatures, the sulfuric acid does not attack the oxide as fast as at elevated temperatures. Because of the lower temperature, the voltages needed to maintain the higher current densities also help form smaller, more dense pores, thus accounting for the hardness and excellent abrasion resistance.

Normal low temperature hardcoating is carried out under the following conditions:

Acid concentration, 180-225 g/L
Aluminum content, 4-15 g/L
Temperature, 28–32°F

There have been a number of organic additives developed in the past few years that allow the anodizer to hardcoat at elevated temperatures (50–70°F). These additives, by virtue of their chemical reaction in the oxide pores, help cool the material being anodized and retard acid dissolution of the coating.

COLORING OF ANODIC COATINGS

The coloring of anodic oxides is accomplished by using organic and inorganic dyes, electrolytic coloring, precipitation pigmentation, or combinations of organic dyeing and electrolytic coloring. After the anodizing step, the parts are simply immersed in the subject bath for coloring.

The thickness of the anodic oxide can range from 0.1 mil for pastel shades up to 1.0 mil for very dark shades and blacks. Application of electrolytic coloring will be discussed below. Suffice it to say, the combination of organic dyeing and electrolytic coloring gives a more complete palette of colors from which to choose.

Organic Dyes

The actual process of dyeing the aluminum oxide is very simple. A water solution of 0.025 to 1.0% of dyestuff at a temperature of 140°F composes the dyebath. The aluminum, previously anodized, is simply immersed in this bath for a short period of time, usually 10 to 30 minutes, The work is then sealed and is resistant to further dyeing or staining.

The equipment required, in addition to that needed for the actual anodizing operation, consists of rinse tanks with clean, flowing water; a dye tank for each color desired; and a sealing bath preferably equipped with continuous filtration.

The dye tanks must be of stainless steel, plastic, fiberglass, or some other inert substance; never of copper or steel. They must be supplied with means of maintaining a constant 140°F temperature and should be equipped with some form of agitation. Usual plant practice is to use air agitation; however, with proper filtration, the filter itself can be used as the source of agitation. With air agitation the use of water and oil traps, plus a filter on the air supply, is

necessary to prevent contamination of the dye solution. A few drops of oil spread on the surface of the dyebath is very often the cause of streaked and spotted work. Typically, the use of blower air agitation is preferred over compressed air.

Rinsing after anodizing, followed by immediate dyeing, is of prime importance. Since some dyes will not dye aluminum in the presence of sulfate ion, poor rinsing can cause streaks and discolorations. Even in the case of dyes not affected by sulfates, any carry-over of acid causes a lowering of the pH of the dyebath, which means shade variations in succeeding batches of work.

In the design of parts to be color anodized, care must be taken to avoid the use of closed heads or seams, which are impossible to rinse. In the case of parts containing recesses, which are difficult to rinse, a neutralizing bath of sodium bicarbonate is of value. In working with coated racks, care must be taken that the rack coating does not separate, thereby forming pockets that can entrap sulfuric acid, later allowing it to seep out into the dyebath. Work must not be allowed to stand in the rinse tanks between anodizing and dyeing, but should be dyed immediately, following a thorough rinsing. For most effective rinsing, three tanks should be used. In this way the final tank, usually deionized water, will remain relatively free of acid.

The variables in the dyebath are time, temperature, concentration, and pH. Time and temperature are readily controlled in plant practice; however, regulation of concentration presents some difficulties. Fortunately, in the case of most single component dyes, concentration control is not very critical, a variation of 100% causing little change in depth of shade.

The usual dyebath concentration for full shades is 2 g/L except for black, which requires from 6 to 10 g/L. In the case of pastel shades concentrations of considerably less than 2 g/L may be required in order that the shade does not become too deep. This reduction in concentration will have a negative effect on the dye lightfastness.

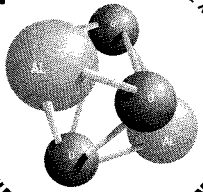
Control of pH is important and a daily check (more often in smaller tanks or where high volume is a factor) should be made. The pH range between 6.0 and 7.0 gives the best results with the majority of dyes; however, a few are more effective at values close to 5.0. Initial adjustments should always be made since it is not practical for the manufacturer to standardize the dyes with respect to the pH of their solutions. These adjustments are made by addition of small amounts of acetic acid to lower the pH value and dilute sodium hydroxide or acetate to raise it. Solutions may be buffered against possible carry-in of sulfuric acid by adding 1 g/L of sodium acetate and adding sufficient acetic acid to reduce the pH to the desired value.

COLORFASTNESS OF THE DYED COATING

Of the many dyes that color anodized aluminum, possibly several hundred, it should be understood that only a few possess sufficient inherent resistance to fading to be considered for applications where exposure to direct sunlight is intended. Where items of long life expectancy are involved, for example, architectural components, even greater selectivity must be imposed, since all organic colorants now known will exhibit some fading when subjected to sunlight of sufficient intensity and duration. Also, the parameters of application as well as the colorant are involved in the resistance to premature loss or change of color. The following additional factors are considered by most authorities as affecting the lightfastness of the dyed coating.

Coating Thickness and Penetration of the Dyestuff

Accelerated and long-term exposure tests and practical experience both here and abroad verify that an anodic oxide thickness in the order of 0.8 mil (20 microns) and its complete penetration by the colorant is required for optimum resistance to fading and weathering. This means that, in some applications, the dye time may be extended to 30 minutes for complete dye saturation.



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Intensity of Shade

Usually, the greater the amount of dye absorbed, the better its resistance to fading. Also, whatever fading may occur will be less apparent to the observer. Pastel shades may, therefore, be expected to exhibit inferior light and weather fastness as compared to full strength dyeing.

Type and Degree of Sealing

Those dyes that are reactive with the nickel or cobalt salts present in the sealing bath usually require this treatment for optimum performance. It is reported that certain selected dyestuffs benefit from after-treatment with other heavy metals; for example, lead, copper, zinc, or chromium. Generally, such treatments are not utilized because of the requirement of an individual sealing tank for each dye.

In the case of extremely porous anodic oxides, for example, those formed on alloys of high copper content, effective sealing is particularly important with certain dyes to prevent color loss from sublimation of the dye or by chemical reaction in oxidizing or reducing environments.

ELECTROLYTIC COLORING (2-STEP)

This electrolytic coloring process consists of conventional sulfuric acid anodizing followed by an AC treatment in a bath containing tin, nickel, cobalt, or other metal salts to produce a series of bronze to black colors as well as blues, greens, burgundies, and golds. The most common bath is one containing tin. The colors produced are not alloy or thickness dependent and are easier to control. The process is not as energy intensive as the integral color process. It is for this reason that this process has almost entirely replaced the integral color process in recent years. Unlike sulfuric acid anodizing, the coloring process is controlled by voltage and time, rather than by current density. Depending upon the bath used, the coloring time can range from 20 sec for champagne to 10 min for black. The use of specially built AC power supplies, using electronic timing and voltage control, helps produce a finish that is reproducible time after time. Proprietary baths containing bath stabilizers, color enhancers, and other additives are being marketed and used throughout the finishing industry.

PIGMENTATION BY PRECIPITATION OF INSOLUBLE COMPOUNDS

Before the development of special organic dyes for coloring anodized aluminum, the precipitation of various insoluble metal compounds within the anodic oxide was used commercially. The treatment consisted of alternatively immersing the anodized surface in concentrated solutions of suitable metal salts until a sufficient amount of the pigment was precipitated to produce the desired color. Although seldom used in today's state of the art, a number of these reactions are listed below:

Lead nitrate (or acetate) with potassium dichromate—yellow
Lead nitrate (or acetate) with potassium permanganate—red
Copper sulfate with ammonium sulfide—green
Ferric sulfate with potassium ferrocyanide—blue
Cobalt acetate with ammonium sulfide—black

Ferric oxalates (ferric ammonium oxalate or ferric sodium oxalate) applied to conventional anodic oxides in the same manner as organic dyes are, under proper conditions, hydrolyzed to deposit ferric hydroxide within the coating pores, imparting a gold to orange color of outstanding resistance to fading. Special proprietary chemicals are available for this treatment.

The deposit of ferric oxide produced in the above manner may, in addition, be converted to ferric sulfide, the resultant shade of which is black. Alternatively, a bronze shade may be formed by reduction of the ferric oxide with pyrogallic acid.

Cobalt acetate reduction, although commercially used in Europe, is not well known in the U.S. It consists of saturating a conventional anodic oxide with the cobalt solution and then reacting this with potassium permanganate to produce a cobalt-manganese dioxide complex. The resultant bronze shade has excellent lightfastness and offers some potential for architectural applications.

MULTICOLOR ANODIZING

The application of two or more colors for the production of nameplates, instrument panels, automotive and appliance trim, etc. has now achieved sufficient commercial importance that a number of large firms deal exclusively with such items.

The following methods of multicolor anodizing are possible:

The *multiple anodizing process,* which entails a complete cycle of anodizing, dyeing, and sealing; application of a resist to selected areas; stripping of the entire anodic oxide from the remaining unprotected surfaces; and repetition of this entire procedure for each color.

The *single anodizing method,* wherein an anodic oxide of sufficient thickness and porosity to absorb the dye required for the darkest shade is first applied. This oxide is then dyed and left unsealed, a resist applied, and the dye alone discharged or bleached out with a solution that leaves the anodic oxide intact. The operation is then repeated for each successive shade. Finally, the resist is removed with a suitable solvent, and the entire surface sealed. In certain cases, where a dark shade is to be applied after a pastel shade, a modification of this technique omits the bleaching step with the supplementary dye being applied directly over the preceding color.

The use of a *specialized combination ink-and-resist* enables information or designs to be printed directly on the previously formed anodic oxide in several colors. The background color may then be applied by conventional dyeing methods, while the ink serves as a stop-off for the printed areas.

Preanodized, photo-sensitized aluminum alloy material is available, wherein the image, in black, may be produced by photographic methods, and the background colored by the conventional dye immersion method.

SEALING OF ANODIC COATINGS

Hydrothermal Sealing (200–212°F)

To achieve the maximum protective qualities and corrosion resistance required for finished articles, the anodic oxide must be sealed after it is formed and/or colored. The sealing process consists of immersing the anodized parts in a solution of boiling water or other solution such as nickel acetate, wherein the aluminum oxide is hydrated. The hydrated form of the oxide has greater volume than the unhydrated form and thus the pores of the coating are filled or plugged and the coating becomes resistant to further staining and corrosion. The use of nickel containing seals will, in most cases, prevent leaching of dyes during the sealing operation.

When sealing with the nickel acetate bath, a smutty deposit may form on the work. This can be minimized by the addition of 0.5% boric acid to the bath or by the use of acetic acid to lower the pH of the solution to 5.3 to 5.5. Too low a pH, however, causes leaching out of the dye. Use of 0.1% wetting agent in this bath also aids in preventing formation of the smut. Proprietary sealing materials designed to completely eliminate this smut are now available from chemical suppliers.

The sealing tank should be of stainless steel or other inert material and must be maintained at 200°F. Use of a filter enables a number of colors to be sealed in the same bath without danger of contamination.

Mid-Temperature Sealing (160–190°F)

Due to the higher energy costs inherent in hydrothermal sealing, chemical manufacturers have developed "mid-temperature" seals (160–190°F). These seals, which contain metal salts such as nickel, magnesium, lithium, and others, have become very popular due to the lower energy costs and their ease of operation.

One disadvantage of the lower temperature is the tendency of organically dyed parts to leach during sealing. This can be compensated for by a slight increase in the bath concentration and by operating the solution at the upper temperature limits (190°F).

"Nickel-free" seals (or more "environmentally friendly" seals, as they are called) are fast becoming the seal of choice where clear or electrolytically colored parts are concerned. Because there is nothing to leach, these mid-temperature seals accomplish hydration of the oxide without the use of the heavy metal ions. When the seals become contaminated or are no longer effective, they can be discharged to the sewer without subsequent treatment (except possible pH adjustment). This offers the finisher a safer alternative to the effluent treating necessary with heavy metal containing seals.

Room Temperature (Cold) Seals (70–90°F)

A significant modification in the sealing of anodized aluminum was the development of "room temperature sealing" (70–90°F). Unlike the high temperature and mid-temperature seals, which depend on hydration for sealing, the cold seals rely on a chemical reaction between the aluminum oxide and the nickel fluoride contained in the seal solution. Unfortunately, this reaction is slow at ambient temperatures and the sealing process can proceed up to 24 hours; however, it has been found that a warm water rinse (160°F) after the cold seal immersion will accelerate the sealing process, allowing for handling and packing of the sealed parts. The sealing of organically dyed parts in cold seals has been found to be advantageous. Light stability testing (fade resistance) has shown that parts sealed in cold seals gain additional lightfastness.

OTHER ELECTROLYTES

A number of other electrolytes are used for specialized applications.

Chromic acid is used in marine environments, on aircraft as a prepaint treatment, and in some cases when finishing assemblies where acid may be entrapped. Although the film produced is extremely thin, it has excellent corrosion resistance and can be colored if desired.

A typical bath might contain from 50 to 100 g/L of chromic acid, and be run at about 95 to 105°F. There are two main processes, one using 40 V and a newer process using 20 V. The equipment needed is similar to that used in sulfuric acid processes.

Oxalic acid is sometimes used as an anodizing electrolyte using similar equipment. This bath will produce films as thick as 2 mils without the use of very low temperatures and usually gives a gold or golden bronze color on most alloys. The typical concentration is from 3 to 10% oxalic acid at about 80 to 90°F, using a DC voltage of about 50 V.

Phosphoric acid baths are used in the aircraft industry as a pretreatment for adhesive bonding. They are also very good treatments before plating onto aluminum. A typical bath might contain from 3 to 20% of phosphoric acid at about 90°F, with voltages as high as 60 V.

SUMMARY

Aluminum is a most versatile metal. It can be finished in a variety of ways. It can be made to resemble other metals, or can be finished to have a colorful as well as a hard, durable finish unique unto itself. Only the imagination limits the finish and colors possible with anodized aluminum.

CHROMATE CONVERSION COATINGS

by Fred W. Eppensteiner (Retired)
and Melvin R. Jenkins

MacDermid Inc., New Hudson, Mich.

Chromate conversion coatings are produced on various metals by chemical or electrochemical treatment with mixtures of hexavalent chromium and certain other compounds. These treatments convert the metal surface to a superficial layer containing a complex mixture of chromium compounds. The coatings are usually applied by immersion, although spraying, brushing, swabbing, or electrolytic methods are also used. A number of metals and their alloys can be treated; notably, aluminum, cadmium, copper, magnesium, silver, and zinc.

The appearance of the chromate film can vary, depending on the formulation of the bath, the basis metal used, and the process parameters. The films can be modified from thin, clear-bright and blue-bright, to the thicker, yellow iridescent, to the heaviest brown, olive drab, and black films. A discussion of specific formulations is not included in this article because of the wide variety of solutions used to produce the numerous types of finishes. It is intended to present sufficient general information to permit proper selection and operation of chromating baths. Proprietary products, which are designed for specific applications, are available from suppliers.

PROPERTIES AND USES

Physical Characteristics

Most chromate films are soft and gelatinous when freshly formed. Once dried, they slowly harden or "set" with age and become hydrophobic, less soluble, and more abrasion resistant. Although heating below 150°F (66°C) is of benefit in hastening this aging process, prolonged heating above 150°F may produce excessive dehydration of the film, with consequent reduction of its protective value. Coating thickness rarely exceeds 0.00005 in., and often is on the order of several microinches. The amount of metal removed in forming the chromate film will vary with different processes.

Variegated colors normally are obtained on chromating, and are due mainly to interference colors of the thinner films and to the presence of chromium compounds in the film. Because the widest range of treatments available is for zinc, coatings for this metal afford an excellent example of how color varies with film thickness. In the case of electroplated zinc, clear-bright and blue-bright coatings are the thinnest. The blue-brights may show interference hues ranging from red, purple, blue, and green, to a trace of yellow, especially when viewed against a white background. Next, in order of increasing thickness, come the iridescent yellows, browns, bronzes, olive drabs, and blacks.

Physical variations in the metal surface, such as those produced by polishing, machining, etching, etc., also affect the apparent color of the coated surface. The color of the thinner coatings on zinc can also be affected indirectly by chemical polishing, making the finish appear whiter.

Corrosion Prevention

Chromate conversion coatings can provide exceptionally good corrosion resistance, depending upon the basis metal, the treatment used, and the film thickness. Protection is due both to the corrosion-inhibiting effect of hexavalent chromium contained in the film and to the physical barrier presented by the film itself. Even scratched or abraded films retain a great deal of their protective value because the hexavalent chromium content is slowly leachable in contact with moisture, providing a self-healing effect.

The degree of protection normally is proportional to film thickness; therefore, thin, clear coatings provide the least corrosion protection, the light iridescent coatings form an intermediate group, and the heavy olive drab to brown coatings result in maximum corrosion protection. The coatings are particularly useful in protecting metal against oxidation that is due to highly humid storage conditions, exposure to marine atmospheres, handling or fingerprint marking, and other conditions that normally cause corrosion of metal.

Bonding of Organic Finishes

The bonding of paint, lacquer, and organic finishes to chromate conversion coatings is excellent. In addition to promoting good initial adhesion, their protective nature prevents subsequent loss of adhesion that is due to underfilm corrosion. This protection continues even thought he finish has been scratched through to the bare metal. It is necessary that the organic finishes used have good adhesive properties, because bonding must take place on a smooth, chemically clean surface; this is not necessary with phosphate-type conversion coatings, which supply mechanical adhesion that is due to the crystal structure of the coating.

Chemical Polishing

Certain chromate treatments are designed to remove enough basis metal during the film-forming process to produce a chemical polishing, or brightening, action. Generally used for decorative work, most of these treatments produce very thin, almost colorless films. Being thin, the coatings have little optical covering power to hide irregularities. In fact, they may accentuate large surface imperfections. In some instances, a leaching or "bleaching" step subsequent to chromating is used to remove traces of color from the film.

If chemical-polishing chromates are to be used on electroplated articles, consideration must be given to the thickness of the metal deposit. Sufficient thickness is necessary to allow for metal removal during the polishing operation.

Absorbency and Dyeing

When initially formed, many films are capable of absorbing dyes, thus providing a convenient and economical method of color coding. These colors supplement those that can be produced during the chromating operation, and a great variety of dyes is available for this purpose. Dyeing operations must be conducted on freshly formed coatings. Once the coating is dried, it becomes nonabsorbent and hydrophobic and cannot be dyed. The color obtained with dyes is related to the character and type of chromate film. Pastels are produced with the thinner coatings, and the darker colors are produced with the heavier chromates. Some decorative use of dyed finishes has been possible when finished with a clear lacquer topcoat, though caution is required because the dyes may not be lightfast.

In a few cases, film colors can be modified by incorporation of other ions or dyes added to the treatment solution.

Hardness

Although most coatings are soft and easily damaged while wet, they become reasonably hard and will withstand considerable handling, stamping, and cold forming. They will not, however, withstand continued scratching or harsh abrasion. A few systems have been developed that possess some degree of "wet-hardness," and these will withstand moderate handling before drying.

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Heat Resistance

Prolonged heating of chromate films at temperatures substantially above 150°F (66°C) can decrease their protective value dramatically. There are two effects of heating that are believed to be responsible for this phenomenon. One is the insolubilization of the hexavalent chromium, which renders it ineffective as a corrosion inhibitor. The second involves shrinking and cracking of the film, which destroys its physical integrity and its value as a protective barrier.

Many factors, such as the type of basis metal, the coating thickness, heating time, temperature, and relative humidity of the heated atmosphere, influence the degree of coating damage. Thus, predictions are difficult to make, and thorough performance testing is recommended if heating of the coating is unavoidable.

The heat resistance of many chromates can be improved by certain posttreatments or "sealers." Baking at paint-curing temperatures after an organic finish has been applied is a normal practice and does not appear to affect the properties of the treatment film.

Electrical Resistance

The contact resistance of articles that have been protected with a chromate conversion coating is generally much lower than that of an unprotected article that has developed corroded or oxidized surfaces. As would be expected, the thinner the coating, the lower the contact resistance, i.e., clear coatings have the least resistance, iridescent yellow coatings have slightly more, and the heavy, olive drab coatings have the greatest. If exposure of an article to corrosive conditions is anticipated, the choice of a coating thickness normally involves a compromise between a very thin film—which, although having very low initial contact resistance, is likely to allow early development of high electrical resistance corrosion products—and a heavier film, with somewhat higher initial contact resistance, but which is likely to remain relatively constant for a longer period under corrosive conditions.

Fabrication

Resistance Welding. Thin chromate films do not interfere appreciably with spot, seam, or other resistance-welding operations. Aluminum coated with a thin, nearly colorless film, for example, can be spot welded successfully with no increase in welding machine settings over those required for bare metal. Metal coated with thicker, colored films also can be resistance welded. The increased contact resistance of thicker coatings, however, necessitates using slightly higher machine settings.

Fusion Welding. These operations, likewise, are not hampered by the presence of chromate films. It has been reported, in fact, that chromate treatments on aluminum actually facilitate inert gas welding of this metal and its alloys, producing contamination-free welds.

Soldering. Cadmium and silver surfaces coated with thin chromate films can be soldered without difficulty using a mild organic flux. Conflicting reports exist regarding the solderabilty of chromated zinc surfaces.

Mechanical Fastening. The assembly of chromated parts using bolts, rivets, and other mechanical fastening devices usually results in local damage to the chromate film. Corrosion protection in these areas will depend upon the effectiveness of the self-healing properties of the surrounding coating.

Summary of Common Uses

Table I summarizes the most common applications of chromate conversion coatings.

MATERIALS OF CONSTRUCTION

Generally, suppliers of proprietaries recommend materials for use with their products, which are resistant to oxidants, fluorides, chlorides, and acids. Materials that have been found

Table I. Common Uses of Chromate Conversion Coatings

	General Usage				
Metal	*Corrosion Resistance*	*Paint Base*	*Chemical Polish*	*Metal Coloring*	*Remarks*
Aluminum	X	X		X	Economical replacement for anodizing if abrasion resistance is not required. Used to "touch-up" damaged areas on anodized surfaces.
Cadmium	X	X	X	X	
Copper	X	X	X	X	Thin coatings prevent "spotting out" of brass and copper electrodeposits. No fumes generated during chemical polishing.
Magnesium	X	X			
Silver	X				
Zinc	X	X	X	X	

to be satisfactory for most chromating applications are stainless steels and plastics. Stainless steels such as 304, 316, 317, and 347 are suitable for tanks and heaters where chlorides are absent. Containers and tank linings can be made from plastics such as polyvinyl chloride (PVC), polyvinylidine chloride (PVDC), polyethylene, and polypropylene. Acid-resistant brick or chemical stoneware is satisfactory for some applications, but is subject to attacks by fluorides.

Parts-handling equipment is made of stainless steel, plastisol-coated mild steel, or plastic.

Mild steel can be used for leaching tanks because the solutions are generally alkaline, whereas tanks for dyeing solutions, which are slightly acid, should be of acid-resistant material.

Usually, ventilation is not necessary because most chromate solutions are operated at room temperature and are nonfuming. Where chromating processes are heated, they should be ventilated.

FILM FORMATION

Mechanism

The films in most common use are formed by the chemical reaction of hexavalent chromium with a metal surface in the presence of other components, or "activators," in an acid solution. The hexavalent chromium is partially reduced to trivalent chromium during the reaction, with a concurrent rise in pH, forming a complex mixture consisting largely of hydrated basic chromium chromate and hydrous oxides of both chromium and the basis metal. The composition of the film is rather indefinite, because it contains varying quantities of the reactants, reaction products, and water of hydration, as well as the associated ions of the particular systems.

There are a number of factors that affect both the quality and the rate of formation of chromate coatings. Of the following items, some are peculiar to chromating; many derive simply from good shop practice. A working understanding of these factors will be helpful in obtaining high-quality, consistent results. Different formulations are required to produce satisfactory chromate films on various metals and alloys. Similarly, the characteristics of the chromate film produced by any given solution can vary with minor changes in the metal or alloy surface. Commonly encountered examples of this follow.

Effect of Basis Metals

Aluminum Alloys. The ease with which coatings on aluminum can be produced, and the degree of protection afforded by them, can vary significantly with the alloying constituents and/or the heat treatment of the part being processed. In general, low alloying constituent metals that are not heat treated are easiest to chromate and provide the maximum resistance to corrosion. Conversely, wrought aluminum, which is high in alloying elements (especially silicon, copper, or zinc) or which has undergone severe heat treatment, is more difficult to coat uniformly and is more susceptible to corrosive attack. High silicon casting alloys present similar problems. The effect of these metal differences, however, can be minimized by proper attention to the cleaning and pretreatment steps. Most proprietary treatment instructions contain detailed information regarding cleaning, desmutting, etc., of the various alloys.

Magnesium Alloys. As in the case of aluminum, the alloying element content and the type of heat treatment affect the chromating of magnesium. With the exception of the dichromate treatments listed as Type III in Military Specification MIL-M-3171, all of the treatments available can be used on all the magnesium alloys.

Zinc Alloys. Chromate conversion coatings on zinc electroplate are affected by impurities codeposited with the zinc. For example, dissolved cadmium, copper, and lead in zinc plating solutions can ultimately cause dark chromated films. Similarly, dissolved iron in noncyanide zinc plating solutions can create chromating problems. Furthermore, the activity of zinc deposits from cyanide and noncyanide solutions can differ sufficiently to produce variations in the chromate film character.

Variations in the composition of zinc die casting alloys and hot-dipped galvanized surfaces can also affect chromate film formation; however, in the latter case, the result is usually difficult to predict, due to the wide variations encountered in spelter composition, cooling rates, etc. Large differences in the chromate coating from spangle to spangle on a galvanized surface are not uncommon. This is especially evident in the heavier films.

Copper Alloys. Since chromate treatments for copper and its alloys can be used to polish chemically as well as to form protective films, the grain structure of the part becomes important, in addition to its alloying content. Whereas fine-grained, homogeneous material responds well to chromate polishing, alloys such as phosphor bronze and heavily leaded brass usually will acquire a pleasing but matte finish. In addition, treatment of copper alloys, which contain lead in appreciable amounts, may result in the formation of a surface layer of powdery, yellow lead chromae.

Effects of pH

One of the more important factors in controlling the formation of the chromate film is the pH of the treatment solution. For any given metal/chromate solution system, there will exist a pH at which the rate of coating formation is at a maximum. As the pH is lowered from this point, the reaction products increasingly become more soluble, tending to remain in solution rather than deposit as a coating on the metal surface. Even though the rate of metal dissolution increases, the coating thickness will remain low. Chemical-polishing chromates for zinc, cadmium, and copper are purposely operated in this low pH range to take advantage of the increased rate of metal removal. The chromate films produced in these cases can be so thin that they are nearly invisible. Beyond this point, further lowering of the pH is sufficient to convert most chromate treatments into simple acid etchants.

Increasing the pH beyond the maximum noted above will gradually lower the rate of metal dissolution and coating formation to the point at which the reaction, for all practical purposes, ceases.

Hexavalent Chromium Concentration

Although the presence of hexavalent chromium is essential, its concentration in many treatment solutions can vary widely with limited effect, compared with that of pH. For

example, the chromium concentration in a typical aluminum treatment solution can vary as much as 100% without substantially affecting the film-formation rate, as long as the pH is held constant. In chromating solutions for zinc or cadmium, the hexavalent chromium can vary fairly widely from its optimum concentration if the activator component is in the proper ratio and the pH is constant.

Activators

Chromate films normally will not form without the presence of certain anions in regulated amounts. They are commonly referred to as "activators' and include acetate, formate, sulfate, chloride, fluoride, nitrate, phosphate, and sulfamate ions. The character, rate of formation, and properties of the chromate film vary with the particular activator and its concentration. Consequently, many proprietary formulations have been developed for specific applications and they are the subject of numerous patents. Usually, these proprietary processes contain the optimum concentrations of the activator and other components; therefore, the user need not be concerned with the selection, separate addition, or control of the activator.

OPERATING CONDITIONS

In addition to the chemical make-up of the chromating solution, the following factors also govern film formation. Once established for a given operation, these parameters should be held constant.

Treatment Time. Immersion time, or contact time of the metal surface and the solution, can vary from as little as 1 second to as much as 1 hour, depending on the solution being used and metal being treated. If prolonged treatment times are required to obtain desired results, a fault in the system is indicated and should be corrected.

Solution Temperature. Chromating temperatures vary from ambient to boiling, depending on the particular solution and metal being processed. For a given system, an increase in the solution temperature will accelerate both the film-forming rate and the rate of attack on the metal surface. This can result in a change in the character of the chromate film. Thus, temperatures should be adequately maintained to ensure consistent results.

Solution Agitation. Agitation of the working solution, or movement of the work in the solution, generally speeds the reaction and provides more uniform film formation. Air agitation and spraying have been used for this purpose. There are, however, a few exceptions where excessive agitation will produce unsatisfactory films.

Solution Contamination

Although the presence of an activator in most treatment solutions is vital, an excessive concentration of this component, or the presence of the wrong activator, can be very detrimental. Most metal-finishing operations include sources of potential activator contamination in the form of cleaners, pickles, deoxidizers, and desmutters. Unless proper precautions are taken, the chromate solution can easily become contaminated through drag-in of inadequately rinsed parts, drippage from racks carried over the solution, etc.

A common source of contamination is that resulting from improperly cleaned work. If allowed to go unchecked, soils can build on the surface of the solution to the point at which even clean work becomes resoiled on entering the treatment tank, resulting in blotchy, uneven coatings.

Other contaminants to be considered are those produced by the reactions occurring in the treatment solution itself. With very few exceptions, part of the trivalent chromium formed and part of the basis metal dissolved during the coating reaction remain in the solution. Small amounts of these contaminants can be beneficial, and "broken-in" solutions often produce more consistent results. As the concentration of these metal contaminants increases, effective film formation will be inhibited. For a certain period, this effect can be counteracted by adjustments, such as lowered pH and increased hexavalent chromium concentration. Eventually, even these techniques become ineffective, at which point the solution must be discarded or a portion withdrawn and replaced with fresh solution.

Rinsing and Drying

Once a chromate film has been formed satisfactorily, the surface should be rinsed as soon as possible. Transfer times from the chromating stage to the rinsing stage should be short in order to minimize the continuing reaction that takes place on the part.

Although rinsing should be thorough, this step can also affect the final character of the chromate film and should be controlled with respect to time and temperature, for consistent results.

Prolonged rinsing or the use of very hot rinsewater can dissolve, or leach, the more soluble hexavalent chromium compounds from a freshly formed coating, resulting in a decrease in protective value. If a hot rinse is used to aid drying, avoid temperatures over about 150°F (66°C) for more than a few seconds. This leaching effect sometimes is used to advantage. In instances in which a highly colored or iridescent coating may be objectionable, a prolonged rinse in hot water can be used as a "bleaching" step to bring the color to an acceptable level. Instead of hot water leaching, some systems incorporate dilute acids and alkalis to accelerate this step.

Solution Control

Because most chromate processes are proprietary, it is suggested that the suppliers' instructions be followed for solution make-up and control. Even though specific formulations will not be discussed, certain general principles can be outlined, which apply generally to chromate solutions. The combination of hexavalent chromium concentration, activator type and concentration, and pH, i.e., the "chemistry" of the solution, largely determines the type of coating that will be obtained, or whether a coating can be obtained at all, at given temperatures and immersion times. It is important that these factors making up the "chemistry" of the solution be properly controlled. As the solution is depleted through use, it is replenished by maintenance additions, as indicated by control tests or the appearance of the work.

Fortunately, analysis for each separate ingredient in a chromate bath is not necessary for proper control. A very effective control method uses pH and hexavalent chromium analysis. The pH is determined with a pH meter and the chromium is determined by a simple titration. Indicators and pH papers are not recommended because of discoloration by the chromate solution. Additions are made to the solution to keep these two factors within operating limits. The amount of control actually required for a given treatment depends on how wide its operating limits are, and on the degree of uniformity of results desired. Control by pH alone is adequate in some cases.

COATING EVALUATION

Chromate conversion coatings are covered by many internal company standards and/or U.S. government and American Society for Testing and Materials (ASTM) specifications. These standards usually contain sections on the following methods of evaluation.

Table II. Typical Salt Spray Data for Electroplated Zinc

Treatment	*Hours to White Corrosion*
Untreated	<8
Clear chromate	24–100
Iridescent yellow	100–200
Olive drab	100–500

Visual Inspection

The easiest way to evaluate chromate conversion coatings is to observe the color, uniformity of appearance, smoothness, and adhesion. Type of color and iridescence is a guide to film thickness, which is considered proportional to protective value; however, visual inspection by itself is not sufficient to indicate the protective value of the coating, especially if the film has been overheated during drying.

Accelerated Corrosion Test

The salt spray test, ASTM B 117, is the most common accelerated test developed in specification form. Although some disagreement exists as to the correlation of salt spray tests to actual performance, it remains in many specifications. Variations in results are often obtained when tested in different salt spray cabinets, and even in different locations within the same cabinet. Coatings should be aged for at least 24 hours before testing, for consistent results. Generally, specifications require a minimum exposure time before visible corrosion forms. Typical salt spray test data are provided in Tables II to IV.

Humidity Tests

There appears to be no standard specification covering humidity tests for unpainted chromate conversion coatings. Evaluations are conducted under various conditions and cycles. Humidity tests may be more useful than salt spray tests, as they correspond to the normal environment better than the salt spray, except in marine atmospheres.

Table III. Typical Salt Spray Data for Copper and Brass

Treatment	*Hours to Green Corrosion*
Copper, untreated	<24
Copper, bright chromate	24
Copper, heavy chromate	50
Brass, untreated	24
Brass, bright chromate	100
Brass, heavy chromate	150

Table IV. Typical Salt Spray Data for Aluminum

	Hours to White Corrosion		
Alloy	*No Treatment*	*Clear*	*Yellow-Brown*
3003	24	60–120	250–800
2024[a]	<24	40–80	150–600
413.0	<24	12–24	50–250

[a] Heat treatment will affect the final results.

Water Tests

Immersion tests in distilled or deionized water have proven valuable in simulating such conditions as water accumulation in chromated zinc die castings, e.g., carburetors and fuel pumps.

Coatings applied on hot-dipped galvanized surfaces in strip mills are often tested by stacking wet sheets and weighing the top sheet. Periodic checks are made to determine when corrosion products first develop. The tests should be conducted at relatively constant temperatures to ensure consistent results.

Chemical and Spot Tests

The amount of hexavalent chromium in the film can be an indication of the corrosion protection afforded by the coating. Analytical procedures for small amounts of chromium on treated surfaces are comparatively rapid, quantitative, and reproducible. Consequently, chemical analysis for the chromium content of the film appears to be a valuable tool. It would not be suitable, however, for predicting the performance of bleached, overheated, excessively dehydrated coatings.

Total coating weight is sometimes used as an indication of corrosion resistance. It is derived by weighing a part having a known surface area before and after chemically stripping only the chromate film.

Spot tests are used to test corrosion resistance by dissolving the chromate coating and reacting with the basis metal. The time required to produce a characteristic spot determines empirically the film thickness or degree of corrosion protection. It is advisable to use these tests as comparative tests only, always spotting an untreated and treated surface at the same time. Frequently, the spot tests are sufficient only to indicate differences between treated and untreated surfaces. Reproducibility is not good because aging affects the results.

Performance Tests for Organic Finishes

Paint, lacquer, and other organic finishes on chromate conversion coatings are tested in numerous ways to evaluate bonding and corrosion protection. These include pencil-hardness, cross-hatch, bending, impact, and tape tests with or without prior exposure to water or salt spray.

SPECIFICATIONS

A list of the more commonly used specifications covering chromate conversion coatings on different basis metals follows. Only the basic specification or standard number is listed, and reference should be made only to the appropriate revision of any particular document.

Aluminum

AMS 2473—Chemical Treatment for Aluminum Base Alloys—General Purpose Coating
AMS 2474—Chemical Treatment for Aluminum Base Alloys—Low Electrical Resistance Coating
ASTM D 1730—Preparation of Aluminum and Aluminum Alloy Surfaces for Painting
MIL-C-5541—Chemical Films and Chemical Film Material for Aluminum and Aluminum Alloys
MIL-C-81706—Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys
MIL-W-6858—Welding, Resistance: Aluminum, Magnesium, etc.; Spot and Seam

Cadmium

AMS 2400—Cadmium Plating
AMS 2416—Nickel-Cadmium Plating, Diffused
AMS 2426—Cadmium Plating, Vacuum Deposition
ASTM B 201—Testing Chromate Coatings on Zinc and Cadmium Surfaces
MIL-C-8837—Cadmium Coating (Vacuum Deposited)
QQ-P-416—Plating, Cadmium (Electrodeposited)

Magnesium

AMS 2475—Protective Treatments, Magnesium Base Alloys
MIL-M-3171—Magnesium Alloy, Process for Pretreatment and Prevention of Corrosion on
MIL-W-6858—Welding, Resistance: Aluminum, Magnesium, etc.; Spot and Seam

Silver

QQ-S-365—Silver Plating, Electrodeposited, General Requirements for

Zinc

AMS 2402—Zinc Plating
ASTM B 201—Testing Chromate Coatings on Zinc and Cadmium Surfaces
ASTM D 2092—Preparation of Zinc-Coated Steel Surfaces for Painting
MIL-A-81801—Anodic Coatings for Zinc and Zinc Alloys
MIL-C-17711—Coatings, Chromate, for Zinc Alloy Castings and Hot-Dip Galvanized Surface
MIL-T-12879—Treatments, Chemical, Prepaint and Corrosion Inhibitive, for Zinc Surfaces
MIL-Z-17871—Zinc, Hot-Dip Galvanizing
QQ-Z-325—Zinc Coating, Electrodeposited, Requirements for

SPECIAL TREATMENTS

Solutions containing chromium compounds are used in some processes where disagreement exists as to whether these form "true" chromate conversion coatings or combination coatings, or act as passivating processes.

Electrolytic Processes

Although early chromate conversion coatings for zinc were electrolytically applied, this method has been largely replaced by immersion processes. More recently, the use of electric current has reappeared with solutions containing mixtures of chromates, phosphates, fluorides, etc., to produce "anodic coatings." The coatings, however, are not similar to anodic coatings such as those produced on aluminum. The coatings on zinc surfaces are complex combinations of chromates, phosphates, oxides, etc. They are formed with 100–200 V AC or

DC, and the fritted coating will withstand more than 1,000 hr of salt spray. The process is used where outstanding corrosion resistance is needed. The coating also exhibits superior hardness, heat resistance, thickness, and dielectric strength when compared with normal chromate conversion coatings. Colors range from dark green to charcoal for different processes.

Electrolytic treatments using chromium compounds are also applied to steel strip, where chromium along with oxides, etc., are deposited in a very thin, discontinuous film. These processes, which promote lacquer and paint adhesion, may be more chromium plate than chromate coating.

Coatings on Beryllium

It has been reported that chromate conversion coatings can be applied to beryllium to retard high-temperature oxidation in humid air.

Chromate-Phosphate Treatments

Chromate-phosphate treatments are based on chromate-phosphate mixtures and form a combination conversion coating on aluminum. The coating can appear practically colorless to a light-green hue. These treatments have been used to impact color for decorative purposes or to provide an imposed base for subsequent lacquer or paint operations.

VACUUM IMPREGNATION

by Stephen M. D'Alfonzo

American Metaseal Corp. of Maryland, Arbutas, Md.

Vacuum impregnation is a valuable metal-finishing process that for some inexplicable reason suffers from near anonymity. The technology has been around since the late 1940s with wide-scale implementation in the early 1950s. It is a procedure utilizing vacuum and pressure to permanently seal porosity in practically all materials with an impregnant, commonly plastic resin.

Casting porosity has always been problematic. It is caused mainly by gas cavitation, foreign inclusions, oxide layers, and internal shrinkage. Voids created by porosity can be found particularly in parts of cast aluminum, zinc, bronze, magnesium, and iron. Powdered metal is like a sponge and is always porous. Porosity is generally classified as either micro or macro. Microporosity is hard to visually detect without a microscope, but macroporosity can usually be seen at the part's surface with the naked eye as obvious imperfections. There are three types of porosity: enclosed porosity, blind porosity, and through porosity.

TYPES OF POROSITY

Enclosed porosity. This a void area that is totally internal and does not pose a problem unless machining exposes it.

Blind porosity. This category can trap finishing solutions, moisture, and atmospheric contaminants that will later leach out and ruin the resultant plated, painted, or otherwise treated finish. Also, internal corrosion can be generated that will prematurely degrade the part from within. This type of porosity causes the most trouble for the metal-finishing industry.

Through porosity. This condition actually allows gases or liquids to pass through the casting wall. These are "leakers."

VACUUM IMPREGNATION

Engineers specify vacuum impregnation for various reasons to address different areas of concern. The most important benefits of the process can be itemized as follows:

1. Restores pressure tightness to leaking parts. The impregnated part will withstand the same pressure as the original casting.
2. Stops internal corrosion before it occurs.
3. Seals brazed assemblies displaying microporosity that cannot be rebrazed.
4. Stops corrosion from occurring between two dissimilar metals that are press-fit together.
5. Improves the bond of press-fit parts.
6. Seals the surface of parts to be plated, painted, or chemically finished to prevent the subsequent bleeding out of entrapped preparation solutions that ultimately destroy the final part quality.

IMPREGNATION MATERIALS

The materials historically used for vacuum impregnation range from the early tung oil, linseed oil, varnish, and sodium silicate to the latest Mil-I-17563B thermocuring and anaerobic methacrylate resins. Heat-curable plastic sealants are most prevalent today, with the Mil-Spec materials exhibiting the best properties.

IMPREGNATION METHODS

Impregnation methods may vary in interpretation, but there are four basic techniques.

Dry Vacuum Pressure

This method starts with parts being lowered into an empty autoclave and a vacuum being pulled to about 29+ inches of mercury for a period of time. The liquid impregnant is introduced to the process chamber. After equalizing, air pressure is applied, usually to about 100 psi. The cycle is complete when the sealant is evacuated from the process autoclave. Parts are now washed, normally in water; and cured. Total processing time is approximately 45 minutes including a hot-water cure at 195°F if the impregnant is a heat-curable methacrylate.

Internal Impregnation

This procedure is suited for very large castings because the part itself becomes the process chamber. All access ports are closed off, and sealant is forced under pressure (no vacuum) into the part's cavity leak paths. After a designated period of time, the impregnant is removed and the part is rinsed and cured. Total cycle time could be 30 minutes plus cure or much longer, depending on the complexity of fixturing.

Wet Vacuum

Anaerobic resins usually require this method, but it is not restricted to just their use. Parts are lowered into an autoclave filled with impregnant, and a vacuum is drawn. The vacuum, at least 28.5 inches of mercury, pulls air from the parts' porosity through the liquid sealant and out of the chamber. There is no air pressure applied but atmospheric. After the vacuum cycle is complete, parts are rinsed and cured. Total process time, not including cure, runs about 30 to 45 minutes. Anaerobic resins cure at room temperature in three hours. A heated 120°F wet cure shortens this to 30 minutes.

Wet Vacuum Pressure

This is the same as wet vacuum, but air pressure up to 100 psi is introduced before the cycle ends. Total time is about 10 minutes longer, depending on personal preference.

The hardware needed for this service is specialized to the industry. Wet vacuum impregnation requires only a vacuum process chamber, up to four rinse tanks, and a hot-water cure tank capable of maintaining 195°F. Anaerobic sealants require refrigeration to 55°F and constant aeration. Heat curables only need light refrigeration to 70°F and no aeration.

Impregnation equipment is not inexpensive, but much depends on the complexity desired. Dry curing, for example, requires the use of ovens maintaining 250°F for heat curables. Fully automatic systems, obviously, are the most costly but are also most efficient.

APPLICATIONS

Vacuum impregnation has for many years been utilized by industry to improve part quality. Automotive and defense applications abound. Once a part or casting is impregnated, the treatment is permanent, with no degradation over time. Navy submarine periscopes have been regularly sealed, as well as exotic drills used on the moon. Typically processed parts include air compressor components, hydraulic pumps and valves, aerospace housings, fuel supply systems, filtration equipment, and the like. In addition, porous substrates are routinely impregnated before plating or painting to guarantee a premium final finish. Since the procedure does not normally involve toxic chemicals, burdensome regulations do not enter the metal-finishing equation. Vacuum impregnation is a solid finishing tool that over the years has helped ensure consistent product quality.

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SOLID FILM LUBRICANTS

by Charles J. Beall

E/M Engineered Coating Solutions, Peachtree City, Ga.

Bonded solid film lubricants are unique products, which utilize the special properties of a variety of lubricating solid materials. Solid film lubricants can generally be defined as solid materials with inherent lubricating properties, which are firmly bonded to the surface of the substrate by some methodology. Perhaps a more simplistic definition might be "slippery paint;" however, this analogy does not begin to describe the diversity of products and processes that have evolved over the years. For example, the bonding methodologies include resin bonding, burnishing, sputtering, ion deposition, and mechanical impingement.

From a commercial standpoint, over 95% of the materials in use today are resin bonded. Typical formulations for resin-bonded solid film lubricants include a lubricating pigment, binder, solvent, and additives to improve corrosion resistance, aesthetics, etc. Formulation considerations, application techniques, typical performance properties, and a few typical applications will be examined in this article.

PIGMENT SELECTION

The primary role of the insoluble solid pigment is generally lubrication. A wide variety of solid materials with inherent lubricating capability is available for use in solid film lubricants. The most commonly used are molybdenum disulfide (MoS_2), graphite, and polytetrafluoroethylene (PTFE) (Table I). While these are the most common, materials such as tungsten disulfide, boron nitride, lead oxide, antimony oxide, niobium selenide, lead, tin, silver, indium, fluorinated ethylene propylene (FEP), perfluoroalkoxy copolymer (PFA), and others are also used.

The selection of the proper pigment or pigment combination is generally governed by the performance that the solid film lubricant formulation must deliver. No single formulation can satisfy all of the requirements on a cost-effective basis. Properties that should be considered are coefficient of friction, load carrying capacity, corrosion resistance (susceptibility to galvanic corrosion), and electrical conductivity. Further, one must consider the environment in which the solid film lubricant must perform. These factors include temperature, pressure, humidity, oxygen content, radiation, etc.

Each of the above solid lubricant materials has strengths and weaknesses in each area and corresponding compromises must be made. Molybdenum disulfide generally has the highest load carrying capability with a corresponding low coefficient of friction; however, in an oxidative atmosphere in excess of 400°C (750°F) MoS_2 begins to decompose. Graphite has high temperature capability in an oxidative environment but tends to promote galvanic corrosion and will not function in high vacuum. The fluorinated polymers such as PTFE generally exhibit a low coefficient of friction and are quite aesthetically suitable for formulations with colored pigments; however, the fluorinated polymers cannot sustain high loading nor do they have good radiation stability.

BINDER SELECTION

As with the pigments, a wide range of resins is available for use as binders or bonding agents in solid film lubricant formulations. These resins carry names similar to the conventional paint resins and are generally of substantially different molecular weight and crosslinking capability. Nevertheless, the organic bonding agents are divided into two types: (1) air-dried, which include acrylics, alkyds, epoxies, vinyls, and acetates and (2) thermosets, including phenolics, epoxy-phenolics, silicones, epoxies, polyamide-imides, and urethanes.

Table I. Properties of Common Lubricating Pigments

Pigment	*Color*	*Load Carrying Capability (psi)*	*Thermal Stability (°F)*
Molybdenum disulfide	Gray-black	>100,000	Good (<750)
Graphite	Gray-black	<50,000	Excellent (<1200)
Polytetrafluoroethylene (PTFE)	White	<6,000	Fair (<500)

	Typical Particle Size (μm)	*Vacuum Suitability*	*Moisture Sensitivity*
Molybdenum disulfide	2–6	Yes	Detrimental
Graphite	2.5–10	No	Necessary
Polytetrafluoroethylene (PTFE)	Submicron	Yes	No effect

Inorganic bonding agents include silicates, phosphates, and ceramics. As with the lubricating pigment selection, the desired physical properties and environment must be considered when selecting the proper product. In addition to the items mentioned above, solvent resistance, corrosion resistance, and cure temperature should also be considered. For example, some of the high temperature curing ceramics may have a deleterious effect on the metallurgical properties of the substrate.

In general, the organic air-dry resins are less expensive to apply, are amenable to field application, and, due to the low cure temperature, have no deleterious effects on metallurgical properties; however, the air-dry resin systems generally have much reduced durability, wear life, and solvent resistance. The oven-cured thermoset resins usually have outstanding durability, solvent resistance, and wear life, but like all organics are subject to radiation damage, vacuum outgassing, limited high temperature applicability, and liquid oxygen incompatibility.

The inorganic binder systems generally have outstanding radiation resistance suitable for extremely high vacuum and high temperature and are compatible with liquid oxygen environments; however, these materials have limited wear life and durability and are often difficult to apply.

PIGMENT/BINDER RATIO

A major consideration in the formulation of solid film lubricant products is the pigment/binder ratio or the amount of lubricating solids to resin solids. Again, the performance requirements and environment are of prime importance. Low pigment-to-binder ratio products have higher coefficients of friction, appear glossy, tend to be hard and durable, and have excellent corrosion resistance. High pigment-to-binder ratio products, on the other hand, generally have a low coefficient of friction, a dull, soft, powdery appearance, and less effective corrosion resistance. Thus, the right pigment-to-binder ratio is necessary to achieve optimum performance.

SOLVENT SELECTION

Solvent selection is generally governed by the evaporation rate and solubility of the resin system; however, other factors must also be considered such as flash point, evaporation rate, toxicity, EPA and OSHA regulations, shipping and storage considerations, etc.

ADDITIVES

Finally, additives can be used in bonded solid film lubricant formulations to enhance a variety of properties such as aesthetics, ease of application, corrosion resistance, etc. Such

Table II. The Effect of Pretreatment on Wear Life

Pretreatment	*LFW-1 Test ASTM D-2714 Cycles to Failure*
None	Failure on loading
Vapor degrease/Sand blast	20,000
Vapor degrease/Sand blast/Phosphate	672,000

additives include dispersants, antisettling agents, wetting agents, flow agents, corrosion inhibitors, and colored pigments or dyes. Generally, these additives are similar to those typically used in the paint industry for similar purposes.

APPLICATION OF RESIN-BONDED PRODUCTS

Once the product has been selected for the desired application, the final step is to assure that the product is properly applied. Generally speaking, 80% of failures of solid film lubricants are due to poor surface pretreatment or other misapplication. To demonstrate the importance of proper pretreatment, the example in Table II was performed.

Three identical Timken T54148 test races were coated with a commercially available phenolic-bonded molybdenum disulfide/graphite-containing product. Coating thicknesses, cure times, and temperatures for all three races were identical. The tests were conducted on an LFW-1 test machine (ASTM D 2714) at 72 rpm and 630-lb load, which corresponds to approximately 100,000 psi.

The only difference between the specimens was the surface pretreatment. The first specimen was vapor degreased and coated with solid film lubricant. The second was degreased and grit blasted with 200-mesh aluminum oxide before coating. The third was degreased, grit blasted, and phosphated with a manganese phosphate conforming to DOD-P-16232 before coating. Table II summarizes the results. Clearly, the preferred pretreatment of degreasing, sand blasting, and phosphating provides the necessary base to achieve the ultimate performance of the solid film lubricant.

While the example in Table II is specific for bearing steel in a particular test, similar results are obtained with a variety of substrates, pretreatments, and solid film lubricants encountered in real applications.

METHODS OF APPLICATION

The methods of applying resin-bonded solid film lubricants are basically identical to those of other paintlike materials; however, resin-bonded solid film lubricants generally need a very tightly controlled film thickness. Unlike conventional paints, the normal recommended thickness is in the range 0.0002–0.0005 in. for optimum wear and lubrication performance; however, other performance factors can require compromise. For example, a thickness of 0.0005–0.0020 in. is preferred for optimum corrosion resistance.

The major factors that govern the selection of method of application of solid film lubricants include the number of parts, size of parts, types of parts, film thickness, tolerance, and functional areas to be coated including masking and overspray allowances. Once these parameters have been defined, it can be determined whether the coating should be applied by conventional-spray equipment, electrostatic spray, dipping, roll coating, brush coating, etc. Generally, spray application with multiple coats provides the best lubrication.

Performance properties of typical bonded solid film lubricants are listed in Table III. While this table is by no means inclusive of all products commercially available, it can provide insight into properties that can be expected.

Table III. Performance Properties of Typical Solid Film Lubricants

	Organic						*Inorganic*		
	Thermo Set				*Air Dry*				
	MIL-L-8937	*MIL-L-46010*			*MIL-L-23398*	*MIL-L-46009*	*MIL-L-81329*	*AMS2525A*	*AMS2526A*
Composition									
Lubricant	MoS_2	MoS_2/ Metallic oxide	MoS_2/ Graphite	PTFE	MoS_2	MoS_2/ Graphite	MoS_2/ Graphite	Graphite	MoS_2
Binder	Phenolic	Epoxy	Silicone	Phenolic			Silicate	—	—
Application	Spray	Spray	Spray	Spray	Spray	Aerosol	Spray		Impingement
Cure	149°C	204°C	260°C	204°C	Ambient	Ambient	204°C	149°C	149°C
Compatibility[a]									
LOX	N/A	N/A	N/A	N/A	N/A	N/A	X	X	X
Oz	N/A	N/A	N/A	N/A	N/A	N/A	X	X	X
Rocket fuel	X	N/A	L	N/A	N/A	N/A	L	X	X
Jet fuel	X	X	X	X	X	L	X	X	X
Hydrocarbons	X	X	X	X	X	L	X	X	X
Solvents	X	X	X	X	X	L	X	X	X
Radiation	Fair	N/A	N/A	N/A	N/A	—	VG	VG	VG
Operating Temp.									
Air (high)	260°C	260°C	371°C	260°C	176°C	204°C	649°C	1,093°C	400°C
Air (low)	−220°C	−220°C	−157°C	−220°C	−220°C	−185°C	−240°C	− 240°C	−220°C
Vacuum	10^{-4}Pa	10^{-7}Pa	10^{-7}Pa	N/A	N/A	N/A	10^{-5}Pa	10^{-7}Pa	10^{-7}Pa
Load capacity[b]									
Force test	2,500 lb gauge Falex	2,500 lb gauge Falex	2,500 lb gauge Falex	150 lb LFW-1	2,500 lb gauge Falex	2,500 lb gauge Falex	—	—	—
Wear life[b]									
Load	1,000 lb gauge	1,000 lb gauge	1,000 lb gauge	150 lb	1,000 lb gauge	—	1,000 lb gauge	50	50
Test	Falex	Falex	Falex	LFW-1	Falex	—	Falex	Falex	Falex
Time	>60 min	>450 min	>60 min	>120,000	>120 min	—	>70 min	>2 min	>5 min
Coefficient of friction	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Corrosion resistance	Good	Very good	Fair	Excellent	Good	—	Fair	—	—

[a] X, compatible; L, low; N/A not applicable.

[b] Falex tests are all designed for English units and are, therefore, reported as such.

CONTROL, ANALYSIS, AND TESTING

CHEMICAL ANALYSIS OF PLATING SOLUTIONS

by Charles Rosenstein
AMZA Ltd., Holon, Israel

and Stanley Hirsch
Leeam Consultants Ltd., New Rochelle, N.Y.

Plating solutions must be routinely analyzed in order to maintain the recommended bath formulation and to preempt the occurrence of problems related to improper levels of bath constituents. Contaminant levels in the solutions must also be monitored. Manufacturers of plating systems establish optimum specifications to ensure maximum solution efficiency and uniformity of deposits. The various factors that cause the concentrations of bath constituents to deviate from their optimum values are as follows:

1. drag-out;
2. solution evaporation;
3. chemical decomposition; and
4. unequal anode and cathode efficiencies.

A current efficiency problem is recognized by gradual but continuous changes in pH, metal content, or cyanide content (see Table I).

The techniques employed for the quantitative analysis of plating solutions are classified as volumetric (titrimetric), gravimetric, and instrumental. Volumetric and gravimetric methods are also known as "wet" methods. The analyst must select the method that is best suited and most cost effective for a particular application.

The wet methods outlined here are simple, accurate, and rapid enough for practically all plating process control. They require only the common analytical equipment found in the laboratory, and the instructions are sufficiently detailed for an average technician to follow without any difficulty. The determination of small amounts of impurities and uncommon

Table I. Problems Caused by Unequal Anode and Cathode Efficiencies

Problem	*Cause*
High pH	High anode efficiency
Low pH	High cathode efficiency
High metal content	High anode efficiency
Low metal content	High cathode efficiency
High free cyanide	Low anode efficiency
Low free cyanide	High anode efficiency

metals should be referred to a competent laboratory, as a high degree of skill and chemical knowledge are required for the determination of these constituents.

Hull cell testing (see the section on plating cells elsewhere in this *Guidebook*) enables the operator to observe the quality of a deposit over a wide current density range.

VOLUMETRIC METHODS

When titrants composed of standard solutions are added to a sample that contains a component whose concentration is to be quantitatively determined, the method is referred to as a volumetric method. The component to be determined must react completely with the titrant in stoichiometric proportions. From the volume of titrant required, the component's concentration is calculated. The simplicity, quickness, and relatively low cost of volumetric methods make them the most widely used for the analysis of plating and related solutions.

Volumetric methods involve reactions of several types: oxidation-reduction, acid-base, complexation, and precipitation. Indicators are auxiliary reagents, which usually signify the endpoint of the analysis. The endpoint can be indicated by a color change, formation of a turbid solution, or the solubilization of a turbid solution.

Some volumetric methods require little sample preparation, whereas others may require extensive preparation. Accuracy decreases for volumetric analyses of components found in low concentrations, as endpoints are not as easily observed as with the components found in high concentrations.

Volumetric methods are limited in that several conditions must be satisfied. Indicators should be available to signal the endpoint of the titration. The component-titrant reaction should not be affected by interferences from other substances found in the solution.

GRAVIMETRIC METHODS

In gravimetric methods, the component being determined is separated from other components of the sample by precipitation, volatilization, or electroanalytical means. Precipitation methods are the most important gravimetric methods. The precipitate is usually a very slightly soluble compound of high purity that contains the component. The weight of the precipitate is determined after it is filtered from solution, washed, and dried. Gravimetric methods are used to supplement the available volumetric methods.

Limitations of gravimetric methods include the requirement that the precipitated component has an extremely low solubility. The precipitate must also be of high purity and be easily filterable.

Species that are analyzed gravimetrically include chloride, sulfate, carbonate, phosphate, gold, and silver.

INSTRUMENTAL METHODS

Instrumental methods differ from wet methods in that they measure a physical property related to the composition of a substance, whereas wet methods rely on chemical reactions. The selection of an instrument for the analysis of plating solutions is a difficult task. Analysts must decide if the cost is justified and if the analytical instrument is capable of analyzing for the required substances with a high degree of accuracy and precision. Instruments coupled to computers can automatically sample, analyze, and record results. Mathematical errors are minimized and sample measurements are more reproducible than with wet methods. Instrumental methods are also extremely rapid when compared with wet methods.

Unlike humans, instruments cannot judge. They cannot recognize improper sample preparation or interfering substances. Erroneous results are sometimes produced by electronic and mechanical malfunctions.

Analytical instruments frequently used in the analysis of plating solutions can be categorized as spectroscopic, photometric, chromatographic, and electroanalytical. Spectroscopic methods (flame photometry, emission spectrometry, X-ray fluorescence, mass spectrometry, and inductively coupled plasma) are based on the emission of light. Photometric methods (spectrophotometry, colorimetry, and atomic absorption) are based on the absorption of light. Chromatographic methods (ion chromatography) involve the separation of substances for subsequent identification. Electroanalytical methods (potentiometry, conductometry, polarography, amperometry, and electrogravimetry) involve an electric current in the course of the analysis.

The instrumental methods, comprehensively reviewed below, are most applicable to plating environments.

SPECTROSCOPIC METHODS

Spectroscopy is the analysis of a substance by the measurement of emitted light. When heat, electrical energy, or radiant energy is added to an atom, the atom becomes excited and emits light. Excitation can be caused by a flame, spark, X-rays, or an AC or DC arc. The electrons in the atom are activated from their ground state to unstable energy shells of higher potential energy. Upon returning to their ground state, energy is released in the form of electromagnetic radiation.

Because each element contains atoms with different arrangements of outermost electrons, a distinct set of wavelengths is obtained. These wavelengths, from atoms of several elements, are separated by a monochromator such as a prism or a diffraction grating. Detection of the wavelengths can be accomplished photographically (spectrograph) or via direct-reading photoelectric detectors (spectrophotometers). The measurement of intensity emitted at a particular wavelength is proportional to the concentration of the element being analyzed.

An advantage of spectroscopy is that the method is specific for the element being analyzed. It permits quantitative analysis of trace elements without any preliminary treatment and without prior knowledge as to the presence of the element. Most metals and some nonmetals may be analyzed. Spectroscopic analysis is also useful for repetitive analytical work.

Disadvantages of spectroscopic analysis include the temperature dependence of intensity measurements, as intensity is very sensitive to small fluctuations in temperature. The accuracy and precision of spectrographic methods is not as high as some spectrophotometric methods or wet analyses. Spectrographic methods are usually limited to maximum element concentrations of 3%. Additionally, sensitivity is much smaller for elements of high energy (e.g., zinc) than for elements of low energy (e.g., sodium).

Applications of spectroscopy include the analysis of major constituents and impurities in plating solutions, and of alloy deposits for composition.

Flame Photometry

In flame photometry (FP), a sample in solution is atomized at constant air pressure and introduced in its entirety into a flame as a fine mist. The temperature of the flame (1,800–3,100°K) is kept constant. The solvent is evaporated and the solid is vaporized and then dissociated into ground state atoms. The valence electrons of the ground state atoms are excited by the energy of the flame to higher energy levels and then fall back to the ground state. The intensities of the emitted spectrum lines are determined in the spectrograph or measured directly by a spectrophotometer.

The flame photometer is calibrated with standards of known composition and concentration. The intensity of a given spectral line of an unknown can then be correlated with the amount of an element present that emits the specific radiation.

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Physical interferences may occur from solute or solvent effects on the rate of transport of the sample into the flame. Spectral interferences are caused by adjacent line emissions when the element being analyzed has nearly the same wavelength as another element. Monochromators or the selection of other spectral lines minimize this interference. Ionization interferences may occur with the higher temperature flames. By adding a second ionizable element, the interferences due to the ionization of the element being determined are minimized.

An advantage of FP is that the temperature of the flame can be kept more nearly constant than with electric sources. A disadvantage of the method is that the sensitivity of the flame source is many times smaller than that of an electric arc or spark.

FP is used for the analysis of aluminum, boron, cadmium, calcium, chromium, cobalt, copper, indium, iron, lead, lithium, magnesium, nickel, palladium, platinum, potassium, rhodium, ruthenium, silver, sodium, strontium, tin, and zinc.

Emission Spectrometry

In emission spectrometry (ES), a sample composed of a solid, cast metal or solution is excited by an electric discharge such as an AC arc, a DC arc, or a spark. The sample is usually placed in the cavity of a lower graphite electrode, which is made positive. The upper counterelectrode is another graphite electrode ground to a point. Graphite is the preferred electrode material because of its ability to withstand the high electric discharge temperatures. It is also a good electrical conductor and does not generate its own spectral lines.

The arc is started by touching the two graphite electrodes and then separating them. The extremely high temperatures (4,000–6,000°K) produce emitted radiation higher in energy and in the number of spectral lines than in flame photometry. Characteristic wavelengths from atoms of several elements are separated by a monochromator and are detected by spectrographs or spectrophotometers. Qualitative identification is performed by using available charts and tables to identify the spectral lines that the emission spectrometer sorts out according to their wavelength. The elements present in a sample can also be qualitatively determined by comparing the spectrum of an unknown with that of pure samples of the elements. The density of the wavelengths is proportional to the concentration of the element being determined. Calibrations are done against standard samples.

ES is a useful method for the analysis of trace metallic contaminants in plating baths. The "oxide" method is a common quantitative technique in ES. A sample of the plating bath is evaporated to dryness and then heated in a muffle furnace. The resultant oxides are mixed with graphite and placed in a graphite electrode. Standards are similarly prepared and a DC arc is used to excite the sample and standards.

X-ray Fluorescence

X-ray fluorescence (XRF) spectroscopy is based on the excitation of samples by an X-ray source of sufficiently high energy, resulting in the emission of fluorescent radiation. The concentration of the element being determined is proportional to the intensity of its characteristic wavelength. A typical XRF spectrometer consists of an X-ray source, a detector, and a data analyzer.

Advantages of XRF include the nondestructive nature of the X-rays on the sample. XRF is useful in measuring the major constituents of plating baths such as cadmium, chromium, cobalt, gold, nickel, silver, tin, and zinc. Disadvantages of XRF include its lack of sensitivity as compared with ES.

X-ray spectroscopy is also used to measure the thickness of a plated deposit. The X-ray detector is placed on the wavelength of the element being measured. The surface of the deposit is exposed to an X-ray source and the intensity of the element wavelength is measured. A calibration curve is constructed for intensity against thickness for a particular deposit. Coating compositions can also be determined by XRF.

Mass Spectrometry

In mass spectrometry (MS), gases or vapors derived from liquids or solids are bombarded by a beam of electrons in an ionization chamber, causing ionization and a rupture of chemical bonds. Charged particles are formed, which may be composed of elements, molecules, or fragments. Electric and magnetic fields then separate the ions according to their mass to charge ratios (*m/e*). The amount and type of fragments produced in an ionization chamber, for a particular energy of the bombarding beam, are characteristic of the molecule; therefore, every chemical compound has a distinct mass spectrum. By establishing a mass spectrum of several pure compounds, an observed pattern allows identification and analysis of complex mixtures.

The mass spectrum of a compound contains the masses of the ion fragments and the relative abundances of these ions plus the parent ion. Dissociation fragments will always occur in the same relative abundance for a particular compound.

MS is applicable to all substances that have a sufficiently high vapor pressure. This usually includes substances whose boiling point is below 450°C. MS permits qualitative and quantitative analysis of liquids, solids, and gases.

Inductively Coupled Plasma

Inductively coupled plasma (ICP) involves the aspiration of a sample in a stream of argon gas, and then its ionization by an applied radio frequency field. The field is inductively coupled to the ionized gas by a coil surrounding a quartz torch that supports and encloses the plasma. The sample aerosol is heated in the plasma, the molecules become almost completely dissociated and then the atoms present in the sample emit light at their characteristic frequencies. The light passes through a monochromator and onto a detector.

The high temperature (7,000°K) of the argon plasma gas produces efficient atomic emission and permits low detection limits for many elements. As with atomic absorption (AA), ICP does not distinguish between oxidation states (e.g., Cr^{3+} and Cr^{6+}) of the same element—the total element present is determined. Advantages of ICP include complete ionization and no matrix interferences as in AA. ICP allows simultaneous analysis of many elements in a short time. It is sensitive to part-per-billion levels.

Disadvantages of ICP include its high cost and its intolerance to samples with greater than 3% dissolved solids. Background corrections usually compensate for interferences due to background radiation from other elements and the plasma gases. Physical interferences, due to viscosity or surface tension, can cause significant errors. These errors are reduced by diluting the sample. Although chemical interferences are insignificant in the ICP method, they can be greatly minimized by careful selection of the instrument's operating conditions, by matrix matching, or by buffering the sample.

ICP is applicable to the analysis of major components and trace contaminants in plating solutions. It is also useful for waste-treatment analysis.

PHOTOMETRIC METHODS

Photometric methods are based on the absorption of ultraviolet (200–400 nm) or visible (400–1,000 nm) radiant energy by a species in solution. The amount of energy absorbed is proportional to the concentration of the absorbing species in solution. Absorption is determined spectrophotometrically or colorimetrically.

The sensitivity and accuracy of photometric methods must be frequently checked by testing standard solutions in order to detect electrical, optical, or mechanical malfunctions in the analytical instrument.

Spectrophotometry and Colorimetry

Spectrophotometry involves analysis by the measurement of the light absorbed by a solution. The absorbance is proportional to the concentration of the analyte in solution. Spectrophotometric methods are most often used for the analysis of metals with concentrations of up to 2%.

Spectrophotometers consist of a light source (tungsten or hydrogen), a monochromator, a sample holder, and a detector. Ultraviolet or visible light of a definite wavelength is used as the light source. Detectors are photoelectric cells that measure the transmitted (unabsorbed) light. Spectrophotometers differ from photometers in that they utilize monochromators, whereas photometers use filters to isolate the desired wavelength region. Filters isolate a wider band of light.

In spectrophotometric titrations, the cell containing the analyte solution is placed in the light path of a spectrophotometer. Titrant is added to the cell with stirring, and the absorbance is measured. The endpoint is determined graphically. Applications of this titration include the analysis of a mixture of arsenic and antimony and the analysis of copper with ethylene diamine tetra acetic acid (EDTA).

The possibility of errors in spectrophotometric analyses is increased when numerous dilutions are required for an analysis.

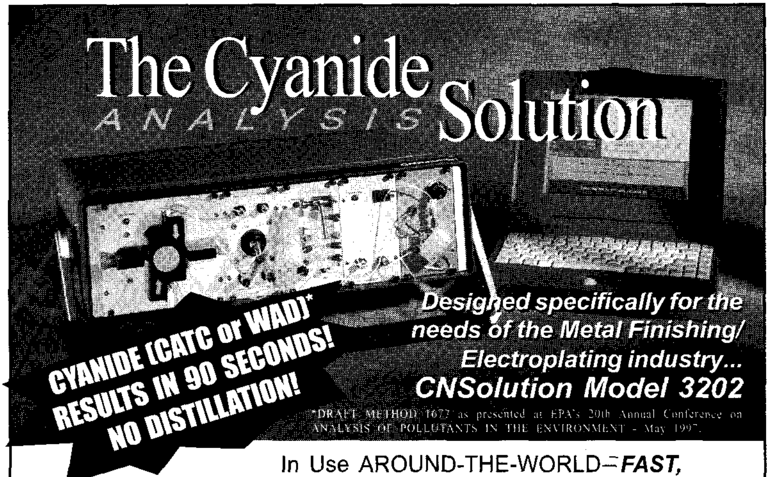
Colorimetry involves comparing the color produced by an unknown quantity of a substance with the color produced by a standard containing a known quantity of that substance. When monochromatic light passes through the colored solution, a certain amount of the light, proportional to the concentration of the substance, will be absorbed. Substances that are colorless or only slightly colored can be rendered highly colored by a reaction with special reagents.

In the standard series colorimetric method, the analyte solution is diluted to a certain volume (usually 50 or 100 ml) in a Nessler tube and mixed. The color of the solution is compared with a series of standards similarly prepared. The concentration of the analyte equals the concentration of the standard solution whose color it matches exactly. Colors can also be compared to standards via a colorimeter (photometer), comparator, or spectrophotometer.

The possible errors in colorimetric measurements may arise from the following sources: turbidity, sensitivity of the eye or color blindness, dilutions, photometer filters, chemical interferences, and variations in temperature or pH.

Photometric methods are available for the analysis of the following analytes:

Anodizing solutions: Fe, Cu, Mn
Brass solutions: Fe
Cadmium solutions: Fe, Ti, Zn, Cu, Ni
Chromium solutions: Cr, Fe, Ni, Cu, Se
Acid copper solutions: Cl, Fe
Alkaline copper solutions: Fe, Se
Gold solutions: Au, Ni, In, Co, Cu, Fe, PO_4
Iron solutions: Mn, NH_3
Lead and tin-lead solutions: Pb
Nickel solutions: Cr, Cu, Zn, Fe, Co, NH_3
Palladium solutions: Pd, Cr, NH_3
Platinum solutions: Pt
Rhodium solutions: Rh
Silver solutions: Ni, Cu, Sb
Acid tin solutions: Fe, Cu
Alkaline tin solutions: Cu, Pb, Zn



Acid zinc solutions: Cu, Fe
Alkaline zinc solutions: Cu, Fe
Wastewater: Cr^{6+}, Ni, Cu, Fe, Zn, Pb, Al, B, NO_3, NO_2, PO_4, Cl, CN, wetting agents.

Atomic Absorption

Metals in plating and related solutions can be readily determined by AA spectrophotometry. Optimum ranges, detection limits, and sensitivities of metals vary with the various available instruments.

In *direct-aspiration atomic absorption* (DAAA) analysis, the flame (usually air-acetylene or nitrous oxide-acetylene) converts the sample aerosol into atomic vapor, which absorbs radiation from a light source. A light source from a hollow cathode lamp or an electrodeless discharge lamp is used, which emits a spectrum specific to the element being determined. The high cost of these lamps is a disadvantage of the AA method. A detector measures the light intensity to give a quantitative determination.

DAAA is similar to flame photometry in that a sample is aspirated into a flame and atomized. The difference between the two methods is that flame photometry measures the amount of emitted light, whereas DAAA measures the amount of light absorbed by the atomized element in the flame. In DAAA, the number of atoms in the ground state is much greater than the number of atoms in any of the excited states of the spectroscopic methods. Consequently, DAAA is more efficient and has better detection limits than the spectroscopic methods.

Spectral interferences occur when a wavelength of an element being analyzed is close to that of an interfering element. The analysis will result in an erroneously high measurement. To compensate for this interference, an alternate wavelength or smaller slit width is used.

When the physical properties (e.g., viscosity) of a sample differ from those of the standard, matrix interferences occur. Absorption can be enhanced or suppressed. To overcome these interferences, matrix components in the sample and standard are matched or a release agent, such as EDTA or lanthanum, is added.

Chemical interferences are the most common interferences encountered in AA analysis. They result from the nonabsorption of molecularly bound atoms in the flame. These interferences are minimized by using a nitrous oxide-acetylene flame instead of an air-acetylene flame to obtain the higher flame temperature needed to dissociate the molecule or by adding a specific substance (e.g., lanthanum) to render the interferant harmless. Chemical interferences can also be overcome by extracting the element being determined or by extracting the interferant from the sample.

The sensitivity and detection limits in AA methods vary with the instrument used, the nature of the matrix, the type of element being analyzed, and the particular AA technique chosen. It is best to use concentrations of standards and samples within the optimum concentration range of the AA instrument. When DAAA provides inadequate sensitivity, other specialized AA methods, such as graphite furnace AA, cold vapor AA, or hydride AA, are used.

In *graphite furnace AA* (GFAA), the flame that is used in DAAA is replaced with an electrically heated graphite furnace. A solution of the analyte is placed in a graphite tube in the furnace, evaporated to dryness, charred, and atomized. The metal atoms being analyzed are propelled into the path of the radiation beam by increasing the temperature of the furnace and causing the sample to be volatilized. Only very small amounts of sample are required for the analysis.

GFAA is a very sensitive technique and permits very low detection limits. The increased sensitivity is due to the much greater occupancy time of the ground state atoms in the optical path as compared with DAAA. Increased sensitivity can also be obtained by using larger sample volumes or by using an argon-hydrogen purge gas mixture instead of nitrogen. Because of its extreme sensitivity, determining the optimum heating times, temperature, and matrix modifiers is necessary to overcome possible interferences.

Interferences may occur in GFAA analysis due to molecular absorption and chemical effects. Background corrections compensate for the molecular absorption interference. Specially coated graphite tubes minimize its interaction with some elements. Gradual heating helps to decrease background interference, and permits determination of samples with complex mixtures of matrix components.

The GFAA method has been applied to the analysis of aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, selenium, silver, and tin.

Cold vapor atomic absorption (CVAA) involves the chemical reduction of mercury or selenium by stannous chloride and its subsequent analysis. The reduced solution is vigorously stirred in the reaction vessel to obtain an equilibrium between the element in the liquid and vapor phases. The vapor is then purged into an absorption cell located in the light path of a spectrophotometer. The resultant absorbance peak is recorded on a strip chart recorder.

The extremely sensitive CVAA procedure is subject to interferences from some organics, sulfur compounds, and chlorine. Metallic ions (e.g., gold, selenium), which are reduced to the elemental state by stannous chloride, produce interferences if they combine with mercury.

Hydride atomic absorption (HAA) is based on chemical reduction with sodium borohydride to selectively separate hydride-forming elements from a sample. The gaseous hydride that is generated is collected in a reservoir attached to a generation flask, and is then purged by a stream of argon or nitrogen into an argon-hydrogen-air flame. This permits high-sensitivity determinations of antimony, arsenic, bismuth, germanium, selenium, tellurium, and tin.

The HAA technique is sensitive to interferences from easily reduced metals such as silver, copper, and mercury. Interferences also arise from transition metals in concentrations greater than 200 mg/L and from oxides of nitrogen.

Ion Chromatography

In ion chromatography (IC), analytes are separated with an eluent on a chromatographic column based on their ionic charges. Because plating solutions are water based, the soluble components must be polar or ionic; therefore, IC is applicable to the analysis of plating and related solutions.

Ion chromatographs consist of a sample delivery system, a chromatographic separation column, a detection system, and a data handling system.

IC permits the rapid sequential analysis of multiple analytes in one sample. The various detectors available, such as UV-visible, electrochemical, or conductivity, allow for specific detection in the presence of other analytes. IC is suitable for the analysis of metals, anionic and cationic inorganic bath constituents, and various organic plating bath additives. It is also used for continuous on-line operations.

Interferences arise from substances that have retention times coinciding with that of any anion being analyzed. A high concentration of a particular ion may interfere with the resolution of other ions. These interferences can be greatly minimized by gradient elution or sample dilution.

IC has been applied to the analysis of the following analytes in plating and related solutions:

Metals: Aluminum, barium, cadmium, calcium, trivalent and hexavalent chromium, cobalt, copper, gold, iron, lead, lithium, magnesium, nickel, palladium, platinum, silver, tin, zinc.

Ions: Ammonium, bromide, carbonate, chloride, cyanide, fluoborate, fluoride, hypophosphite, nitrate, nitrite, phosphate, potassium, sodium, sulfate, sulfide, sulfite.

Acid Mixtures: Hydrofluoric, nitric, and acetic acids.

Organics: Brighteners, surfactants, organic acids.

ELECTROANALYTICAL METHODS

Electroanalytical methods involve the use of one or more of three electrical quantities—current, voltage, and resistance. These methods are useful when indicators for a titration are unavailable or unsuitable. Although trace analysis may be done quite well by spectroscopic or photometric methods, electroanalytical methods offer ease of operation and relatively lower costs of purchase and maintenance.

Potentiometry

Potentiometry involves an electrode that responds to the activity of a particular group of ions in solution. Potentiometric methods correlate the activity of an ion with its concentration in solution.

In potentiometric titrations, titrant is added to a solution and the potential between an indicator and reference electrode is measured. The reaction must involve the addition or removal of an ion for which an electrode is available. Acid-base titrations are performed with a glass indicator electrode and a calomel reference electrode. The endpoint corresponds to the maximum rate of change of potential per unit volume of titrant added.

Advantages of potentiometric titrations include its applicability to colored, turbid, or fluorescent solutions. It is also useful in situations where indicators are unavailable.

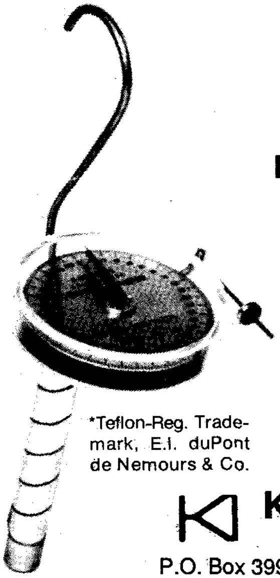
The sensitivity of potentiometric titrations is limited by the accuracy of the measurement of electrode potentials at low concentrations. Solutions that are more dilute than 10^{-5} N cannot be accurately titrated potentiometrically. This is because the experimentally measured electrode potential is a combined potential, which may differ appreciably from the true electrode potential. The difference between the true and experimental electrode potentials is due to the residual current, which arises from the presence of electroactive trace impurities.

The direct potentiometric measurement of single ion concentrations is done with ion selective electrodes (ISEs). The ISE develops an electric potential in response to the activity of the ion for which the electrode is specific. ISEs are available for measuring calcium, copper, lead, cadmium, ammonia, bromide, nitrate, cyanide, sulfate, chloride, fluoride, and other cations and anions.

Cation ISEs encounter interferences from other cations, and anion ISEs encounter interferences from other anions. These interferences can be eliminated by adjusting the sample pH or by chelating the interfering ions. ISE instructions must be reviewed carefully to determine the maximum allowable levels of interferants, the upper limit of the single ion concentration for the ISE, and the type of media compatible with the particular ISE.

Some of the solutions that can be analyzed by potentiometric methods are:

Anodizing solutions: Al, H_2SO_4, $C_2H_2O_4$, CrO_3, Cl
Brass solutions: Cu, Zn, NH_3, CO_3
Bronze solutions: Cu, Sn, NaOH, NaCN, Na_2CO_3
Chromium solutions: Cr, Cl
Cadmium solutions: Cd, NaOH, NaCN, Na_2CO_3
Acid copper solutions: Cl
Alkaline copper solutions: NaOH, NaCN, Na_2CO_3
Gold solutions: Au, Ag, Ni, Cu
Lead and tin/lead solutions: Pb, Sn, HBF_4
Nickel solutions: Co, Cu, Zn, Cd, Cl, H_3BO_3
Silver solutions: Ag, Sb, Ni
Acid tin solutions: Sn, HBF_4, H_2SO_4
Alkaline tin solutions: Sn, NaOH, $NaCO_3$, Cl
Zinc solutions: Zn



Conductometry

Electrolytic conductivity measures a solution's ability to carry an electric current. A current is produced by applying a potential between two inert metallic electrodes (e.g., platinum) inserted into the solution being tested. When other variables are held constant, changes in the concentration of an electrolyte result in changes in the conductance of electric current by a solution.

In conductometric titrations, the endpoint of the titration is obtained from a plot of conductance against the volume of titrant. Excessive amounts of extraneous foreign electrolytes can adversely affect the accuracy of a conductometric titration.

Conductometric methods are used when wet or potentiometric methods give inaccurate results due to increased solubility (in precipitation reactions) or hydrolysis at the equivalence point. The methods are accurate in both dilute and concentrated solutions, and they can also be used with colored solutions.

Conductometric methods have been applied to the analysis of Cr, Cd, Co, Fe, Ni, Pb, Ag, Zn, CO_3, Cl, F, and SO_4.

Polarography

In polarography, varying voltage is applied to a cell consisting of a large mercury anode (reference electrode) and a small mercury cathode (indicator electrode) known as a dropping mercury electrode (DME). Consequent changes in current are measured. The large area of the mercury anode precludes any polarization. The DME consists of a mercury reservoir attached to a glass capillary tube with small mercury drops falling slowly from the opening of the tube. A saturated calomel electrode is sometimes used as the reference electrode.

The electrolyte in the cell consists of a dilute solution of the species being determined in a medium of supporting electrolyte. The supporting electrolyte functions to carry the current in order to raise the conductivity of the solution. This ensures that if the species to be determined is charged, it will not migrate to the DME. Bubbling an inert gas, such as nitrogen or hydrogen, through the solution prior to running a polarogram, will expel dissolved oxygen in order to prevent the dissolved oxygen from appearing on the polarogram.

Reducible ions diffuse to the DME. As the applied voltage increases, negligible current flow results until the decomposition potential is reached for the metal ion being determined. When the ions are reduced at the same rate as they diffuse to the DME, no further increases in current occur, as the current is limited by the diffusion rate. The half-wave potential is the potential at which the current is 50% of the limiting value.

Polarograms are obtained by the measurement of current as a function of applied potential. Half-wave potentials are characteristic of particular substances under specified conditions. The limiting current is proportional to the concentration of the substance being reduced. Substances can be analyzed quantitatively and qualitatively if they are capable of undergoing anodic oxidation or cathodic reduction. As with other instrumental methods, results are referred to standards in order to quantitate the method.

Advantages of polarographic methods include their ability to permit simultaneous qualitative and quantitative determinations of two or more analytes in the same solution. Polarography has wide applicability to inorganic, organic, ionic, or molecular species.

Disadvantages of polarography include the interferences caused by large concentrations of electropositive metals in the determination of low concentrations of electronegative metals. The very narrow capillary of the DME occasionally becomes clogged.

Polarographic methods are available for the following solutions:

Anodizing solutions: Cu, Zn, Mn
Brass solutions: Pb, Cd, Cu, Ni, Zn
Bronze solutions: Pb, Zn, Al, Cu, Ni
Cadmium solutions: Cu, Pb, Zn, Ni

Table II. Reactions That Can Be Analyzed by Amperometry

Analyte	*Titrant*	*Supporting Electrolyte*
Fluoride	Lead nitrate	Potassium chloride
Gold	Hydroquinone	Sulfuric acid
Nickel	Dimethylglyoxime	Chloride
Lead	Sodium fluoride	Chloride
Bromide	Silver nitrate	Nitric acid
Calcium	EDTA	Ammonia
Cadmium	EDTA	Ammonia
Chloride	Silver nitrate	Nitric acid
Indium	EDTA	Weak acid

EDTA, ethylene diamine tetra acetic acid.

Chromium solutions: Cu, Ni, Zn, Cl, SO_4
Acid copper solutions: Cu, Cl
Alkaline copper solutions: Zn, Fe, Pb, Cu
Gold solutions: Au, Cu, Ni, Zn, In, Co, Cd
Iron solutions: Mn
Lead and tin-lead solutions: Cu, Cd, Ni, Zn, Sb
Nickel solutions: Cu, Pb, Zn, Cd, Na, Co, Cr, Mn
Palladium solutions: Pd, Cr^{3+}, Cr^{6+}
Rhodium solutions: Rh
Silver solutions: Sb, Cu, Cd
Acid tin solutions: Sn^{4+}, Cu, Ni, Zn
Alkaline tin solutions: Pb, Cd, Zn, Cu
Acid zinc solutions: Cu, Fe, Pb, Cd
Alkaline zinc solutions: Pb, Cd, Cu
Wastewater: Cd, Cu, Cr^{3+}, Ni, Sn, Zn

Amperometry

Amperometric titrations involve the use of polarography as the basis of an electrometric titration. Voltage applied across the indicator electrode (e.g., DME or platinum) and reference electrode (e.g., calomel or mercury) is held constant and the current passing through the cell is measured as a function of titrant volume added. The endpoint of the titration is determined from the intersection of the two straight lines in a plot of current against volume of titrant added. Polarograms are run to determine the optimum titration voltage.

Amperometric titrations can be carried out at low analyte concentrations at which volumetric or potentiometric methods cannot yield accurate results. They are temperature independent and more accurate than polarographic methods. Although amperometry is useful for oxidation-reduction or precipitation reactions, few acid-base reactions are determined by this method.

Some of the reactions that can be analyzed by amperometric methods are given in Table II.

Electrogravimetry

In electrogravimetry, the substance to be determined is separated at a fixed potential on a preweighed inert cathode, which is then washed, dried, and weighed. Requirements for an accurate electrogravimetric analysis include good agitation, smooth adherent deposits, and proper pH, temperature, and current density.

Table III. Molarities and Normalities of Standard Solutions

Standard Solution	*Formula*	*Normality*	*Molarity*
EDTA	$C_{10}H_{14}O_8N_2Na_2 \cdot 2H_2O$	0.2	0.1
Ferrous ammonium sulfate	$FeSO_4(NH_4)_2SO_4 \cdot 6H_2O$	0.1	0.1
Hydrochloric acid	HCl	1.0	1.0
Iodine	I_2	0.1	0.1
Potassium dichromate	$K_2Cr_2O_7$	0.1	0.02
Potassium iodide-iodate	KI-KIO3	0.1	0.0167
Potassium permanganate	$KMnO_4$	0.1	0.02
Potassium thiocyanate	KSCN	0.1	0.1
Silver nitrate	$AgNO_3$	0.1	0.1
Sodium hydroxide	NaOH	1.0	1.0
Sodium thiosulfate	$Na_2S_2O_3 \cdot 5H_2O$	0.1	0.1

EDTA, ethylene diamine tetra acetic acid.

Advantages of electrogravimetry include its ability to remove quantitatively most common metals from solution. The method does not require constant supervision. Disadvantages include long electrolysis times.

Some of the metals that have been determined electrogravimetrically are cadmium, cobalt, copper, gold, iron, lead, nickel, rhodium, silver, tin, and zinc.

SAMPLING

Analyses are accurate only when the sample is truly representative of the solution being analyzed. Each tank should have a reference mark indicating the correct level for the solution, and the bath should always be at this level when the sample is taken. Solutions should be stirred before sampling. If there is sludge in the tank, the solution should be stirred at the end of the day and the bath allowed to stand overnight, taking the sample in the morning.

Solutions should be sampled by means of a long glass tube. The tube is immersed in the solution, the thumb is placed over the upper open end, and a full tube of solution is withdrawn and transferred to a clean, dry container. The solution should be sampled at a minimum of 10 locations in the tank to ensure a representative sample. A quart sample is sufficient for analysis and Hull cell testing, and any remaining solution can be returned to its tank.

STANDARD SOLUTIONS, REAGENTS, AND INDICATORS FOR WET METHODS

Standard solutions, reagents, and indicators can be purchased ready-made from laboratory supply distributors. Unless a laboratory has the experience and high degree of accuracy that is required in preparing these solutions, it is recommended that they be purchased as prepared solutions. Preparations for all the solutions are given here to enable technicians to prepare or recheck their solutions.

A standard solution is a solution with an accurately known concentration of a substance used in a volumetric analysis. Standardization of standard solutions requires greater accuracy than routine volumetric analyses. An error in standardization causes errors in all analyses that are made with the solution; therefore, Primary Standard Grade chemicals should be used to standardize standard solutions.

The strengths of standard solutions are usually expressed in terms of normality or molarity. Normalities of standard solutions and their equivalent molarities are listed in Table III. The methods to standardize all the standard solutions required for the analysis of plating and related solutions are listed in Table IV.

Indicators are added to solutions in volumetric analyses to show color change or onset of turbidity, signifying the endpoint of a titration. The indicators required for all of the analyses and their preparations are listed in Table V. Analytical Grade chemicals should be used in preparing analytical reagents (Table VI) and Reagent Grade acids should be used (Table VII). When chemicals of lesser purity are used, the accuracy of the results will be diminished.

Tables VIII through XII provide specific methods for testing the constituents of electroplating, electroless, and anodizing baths, as well as acid dips and alkaline cleaners.

SAFETY

As with any laboratory procedure, the accepted safety rules for handling acids, bases, and other solutions should be followed. Acids are always added to water, not the reverse. Mouth pipettes should not be used for pipetting plating solutions. Safety glasses should always be worn, and care should be exercised to avoid skin and eye contact when handling chemicals. A fume hood should be used when an analytical method involves the liberation of hazardous or annoying fumes. Laboratory staff should be well versed in the first-aid procedures required for various chemical accidents.

DETERMINATION OF CATHODE EFFICIENCY

The procedure for determining cathode efficiency, using the setup pictured in Fig. 1, is as follows:

1. Connect the copper coulometer in series with the test cell.
2. The copper coulometer solution should contain 30 oz/gal copper sulfate pentahydrate and 8 oz/gal sulfuric acid.
3. Use the same anodes, temperature, and agitation in the test solution that are used in the plating bath.
4. Plate at 0.4 A (30 A/ft^2) for a minimum of 10 minutes.
5. Rinse both cathodes, dry in acetone, and weigh.

$$\%\ \text{Cathode Efficiency} = \frac{\text{weight in grams of test metal} \times \text{valence of test metal in bath} \times 3177}{\text{weight in grams of copper metal} \times \text{atomic weight of test metal}}$$

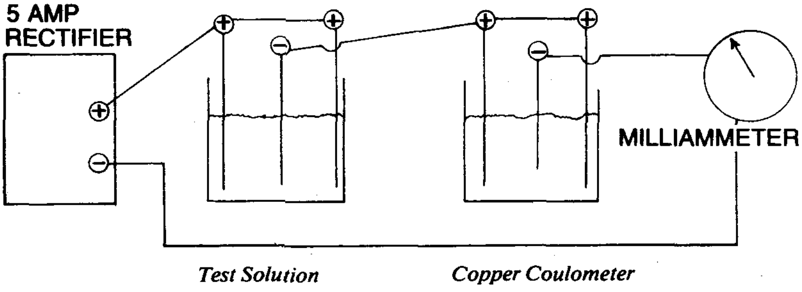


Fig. 1. Test setup for determination of cathode efficiency. Use 500-ml beakers and 1 × 2-in. brass cathodes. The anodes for the test solution should match that used in the plating bath. Use copper anodes for the coulometer.

Table IV. Standardization of Standard Solutions

Solution	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant; wt-sample in grams)*
0.1 M EDTA 37.0 g $Na_2EDTA \cdot 2H_2O$ per liter H_2O	5.0 g $CaCO_3$ dissolved in 1:3 HCl and diluted to 500 ml in a volumetric flask. Pipette 20-ml sample, add 100 ml H_2O,[a] 10 ml pH 10 buffer, and EBT powder.	EDTA	Red-blue	M EDTA = (wt $CaCO_3$ × ml sample)/(ml EDTA × 50.05)
0.1 N HCl 9 ml 36% HCl per liter H_2O	0.2 g Na_2CO_3, 125 ml H_2O, and bromocresol green.	HCl	Blue-green	N HCl = (wt Na_2CO_3)/(ml × 0.05299)
1.0 N HCl 89 ml 36% HCl per liter H_2O	2.0 g Na_2CO_3, 125 ml H_2O, and bromocresol green.	HCl	Blue-green	N HCl = (wt Na_2CO_3)/(ml × 0.05299)
0.1 N I_1 12.7 g I_2, 24.0 g KI per liter H_2O	0.2 g As_2O_3, 20 ml 1.0 N NaOH, gently heat until As_2O_3 dissolves, cool, add phenolphthalein, 1.0 N HCl added from pink to colorless, 100 ml H_2O, 1 ml conc. HCl, 2 g bicarbonate added slowly, and starch solution.	I_2	Colorless-blue	N I_2 = (wt As_2O_3/(ml × 0.04946)
0.01 N $Hg(NO_3)_2$ 1.083 g HgO, 5 ml 50% HNO_3 per liter H_2O	7.5 g KCl dissolved in H_2O and diluted to 1,000 ml in a volumetric flask. Pipette 2-ml sample, add 100 ml H_2O, and 15 ml 20% trichloroacetic acid.	$Hg(NO_3)_2$	Colorless-purple	N $Hg(NO_3)_2$ = (wt KCl × ml sample)/(ml $Hg(NO)_3)_2$ × 74.56)
0.1 N KI-KIO_3 3.6 g KIO_3, 1.0 g NaOH, 10.0 g KI per liter H_2O	In 500-ml flask add 0.20 g Sn, 100 ml conc. HCl, 2 drops $SbCl_3$ solution, let stand at room temperature till dissolved. Add 180 ml H_2O, 5-in. folded "U"-shaped nickel strip, and 5.0 g reduced iron powder. Stopper flask with rubber stopper fitted with ¼-in. glass tube immersed into a saturated $NaHCO_3$ solution. Heat solution on hot-plate to boil for 20 minutes and then place in cooling tank and allow to cool to room temperature. Make sure glass outlet tube is immersed in the $NaHCO_3$. Remove stopper and add starch solution.	KI-KIO_3	Colorless-blue	N KI-KIO_3 = (wt Sn)/(ml × 0.059345)

Table IV. Standardization of Standard Solutions *(cont.)*

Solution	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant; wt-sample in grams)*
0.1 N $KMnO_4$ 3.2 g $KMnO_4$ per liter H_2O	Heat $KMnO_4$ solution to near boiling for 30 minutes and let stand overnight. Filter through a sintered glass crucible. Then, to standardize: add 0.2 g $Na_2C_2O_4$, 200 ml H_2O, 30 ml 20% H_2SO_4, heat to 185–195°F.	$KMnO_4$	Colorless-pink	N $KMnO_4$ = (wt $Na_2C_2O_4$)/(ml × 0.0670)
0.1 N KSCN 9.7 g KSCN per liter H_2O	0.3 g Ag, 15 ml 50% HNO_3, 100 ml H_2O, and FAS.	KSCN	Colorless-red	N KSCN = (wt Ag)/(ml × 0.10787)
0.1 $AgNO_3$ 17.0 g $AgNO_3$ per liter H_2O	0.2 g NaCl, 125 ml H_2O, and K_2CrO_4.	$AgNO_3$	Yellow-red	N $AgNO_3$ = (wt NaCl)/(ml × 0.05845)
0.1 N NaOH 4.0 g NaOH per liter H_2O	0.5 g potassium hydrogen phthalate ($KHC_8H_4O_4$), 125 ml H_2O, and phenolphthalein.	NaOH	Colorless-pink	N NaOH = (wt $KHC_8H_4O_4$)/(ml × 0.20422)
1.0 N NaOH 40.0 g NaOH per liter H_2O	4.0 g potassium hydrogen phthalate ($KHC_8H_4O_4$), 125 ml H_2O, and phenolphthalein indicator.	NaOH	Colorless-pink	N NaOH = (wt $KHC_8H_4O_4$)/(ml × 0.20422)
0.1 N $Na_2S_2O_3$ 25.0 g $Na_2S_2O_3 \cdot 5H_2O$ per liter H_2O	Add 0.1 g Na_2CO_3 to $Na_2S_2O_3$ solution and let stand for 24 hours. To standardize: add 0.12 g KIO_3, 2 g KI, 25 ml H_2O, and 8 ml 10% HCl. Titrate to light yellow with $Na_2S_2O_3$ and add 2 ml starch solution.	$Na_2S_2O_3$	Blue-colorless	N $Na_2S_2O_3$ = (wt KIO_3)/(ml × 0.03567)
0.1 N $Th(NO_3)_4$ 14.0 g $Th(NO_3)_4 \cdot 4H_2O$ per liter H_2O	5.0 g NaF dissolved in H_2O and diluted to 1,000 ml in a volumetric flask. Pipette 10-ml sample, add 100 ml H_2O, alizarin indicator, 2% HNO_3, dropwise from pink to yellow, and 3 ml fluoride buffer.	$Th(NO_3)_4$	Yellow-pink	N = (wt NaF per liter)/(ml × 4.1998)

EDTA, ethylene diamine tetra acetic acid.

[a] Use deionized or distilled water for all solutions.

Table V. Indicators for Analyses

Alizarin	1.0 g sodium alizarin sulfonate, 1,000 ml H_2O.
Bromocresol Green	0.4 g bromocresol green, 1,000 ml H_2O, 0.5 ml 1.0 N NaOH.
Bromocresol Purple	0.4 g bromocresol purple, 1,000 ml H_2O, 1.0 ml 1.0 N NaOH.
EBT Powder	2.0 g Eriochrome Black T, 198 g NaCl.
EBT Solution	5.0 g Eriochrome Black T, 150 ml methanol, 100 ml triethanolamine.
FAS	50 g ferrous ammonium sulfate, 950 ml H_2O, 10 ml conc. HNO_3.
K_2CrO_4	20 g K_2CrO_4, 980 ml H_2O.
Methyl Orange	1.0 g methyl orange (sodium salt), 1,000 ml H_2O.
Murexide	2.0 g murexide, 198 g NaCl.
PAN	1.0 g peroxyacetal nitrate, 1,000 ml methanol.
Phenolphthalein	1.0 g phenolphthalein, 500 ml ethanol, 500 ml H_2O.
Starch Solution	10.0 g starch, 1,000 ml hot H_2O, 0.5 ml formaldehyde.
Sulfo Orange	100 ml sulfo orange, 100 g NaCN, 845 ml H_2O.

Note: Use deionized or distilled water for preparation of all solutions.

Table VI. Reagents for Analyses

Ammonium Oxalate Solution	40 g ammonium oxalate, 960 ml H_2O.
Dimethylglyoxime Solution	10 g dimethylglyoxime, 1,000 ml ethanol.
Fluoride Buffer	Dissolve 40 g monochloroacetic acid in 400 ml H_2O and divide the solution in two equal parts. Add phenolphthalein to one part and titrate with 1.0 N NaOH from colorless to pink. Mix both parts and add H_2O to 1,000 ml.
KF Solution	100 g KF dissolved in 1,000 ml H_2O. Neutralize to pH 7.0 with 1.0 N NaOH.
NaCN Solution	100 g NaCN, 900 ml H_2O.
Na_2SO_4 Solution	135 g Na_2SO_4, 950 ml H_2O.
pH 10 Buffer	350 ml conc. NH_4OH, 54 g NH_4Cl, 625 ml H_2O.
Reducing Solution	100 ml conc. HCl, 250 ml conc. $HC_2H_3O_2$, 200 ml ethanol, 450 ml H_2O.
Rochelle Solution	200 g Rochelle salts, 800 ml H_2O.
$SbCl_3$ Solution	2.0 g $SbCl_3$, 100 ml 50% HCl.
Silver Nitrate Solution	10 g $AgNO_3$, 95 ml H_2O.
Sodium Sulfite Solution	100 g sodium sulfite, 950 ml H_2O. Adjust to pH 9.0 with 1.0 N NaOH or 1.0 N HCl. Solution has a 1-week shelf life.
Tartaric Acid Solution	150 g tartaric acid, 950 ml H_2O.

Note: Use deionized or distilled water for preparation of all reagents.

Table VII. Properties of Reagent Grade Acids

Acid	*Formula*	*Wt %*	*Specific Gravity (60°F)*	*Pounds/Gallon*
Acetic	$HC_2H_3O_2$	99.0	1.050	8.76
Fluoboric	HBF_4	48.0	1.365	11.38
Formic	$HCHO_2$	98.0	1.220	10.17
Hydrobromic	HBr	48.0	1.490	12.43
Hydrochloric	HCl	36.0	1.183	9.87
Hydrofluoric	HF	70.0	1.256	10.48
Nitric	HNO_3	70.0	1.420	11.84
Phosphoric	H_3PO_4	85.0	1.690	14.09
Sulfuric	H_2SO_4	93.0	1.835	15.30

Table VIII. Test Methods for Electroplating Solutions

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Brass					
CuCN (Method I)	2 ml	15 ml conc. HNO_3, heat to blue color, 100 ml H_2O,[a] conc. NH_4OH to deep blue, heat to 140°F, and add PAN.	0.1 M EDTA	Purple-green	CuCN (oz/gal) = 2.985 × M × [2 × CuCN ml − 0.8 × $Zn(CN)_2$ ml]
CuCN (Method II)	2 ml	100 ml H_2O, 15 ml conc. HNO_3, heat to blue color and disappearance of brown fumes, NH_4OH to deep blue, acetic acid to light blue, 5 g KI. Titrate with $Na_2S_2O_3$ to pale yellow, add 5 ml starch solution, continue titrating to colorless.	0.1 N $Na_2S_2O_3$	Blue-colorless	CuCN (oz/gal) = ml × 5.971 × N
$Zn(CN)_2$	5 ml	100 ml H_2O, 10 ml pH 10 buffer, EBT powder, and 15 ml 10% formaldehyde.	0.1 M EDTA	Red-blue	$Zn(CN)_2$ (oz/gal) = ml × 3.131 × M
NaCN or KCN	5 ml	100 ml H_2O and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	NaCN (oz/gal) = ml × 2.614 × N KCN (oz/gal) = ml × 3.473 × N
NaOH or KOH	5 ml	25 ml H_2O and 5 ml sulfo-orange.	1.0 N HCl	Orange-yellow	NaOH (oz/gal) = ml × 1.067 × N KOH (oz/gal) = ml × 1.496 × N
Na_2CO_3 or K_2CO_3	10 ml	100 ml hot H_2O, 35 ml 10% $Ba(NO_3)_2$, allow to settle, filter, wash filter twice with hot H_2O, transfer filter paper and precipitate to a beaker, add 100 ml H_2O, and methyl orange.	1.0 N HCl	Orange-pink	Na_2CO_3 (oz/gal) = ml × 0.707 × N K_2CO_3 (oz/gal) = ml × 0.921 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
$KNaC_4H_4O_6{\cdot}4H_2O$	5 ml	25 ml 20% H_2SO_4, filter, wash flask and filter paper twice each with H_2O, and boil the collected filtrate 5 minutes.	0.1 N $KMnO_4$	Colorless-pink	$KNaC_4H_4O_6{\cdot}4H_2O$ (oz/gal) = ml × 1.250 × N
Bronze					
Cu (Method I)	2 ml	15 ml conc. HNO_3, heat to blue color, 100 ml H_2O, conc. NH_4OH to deep blue, heat to 140°F and add PAN.	0.1 M EDTA	Purple-green	Cu (oz/gal) = ml × 4.236 × M
Cu (Method II)	2 ml	100 ml H_2O, 15 ml conc. HNO_3, heat to blue color and disappearance of brown fumes, NH_4OH to deep blue, acetic acid to light blue, 5 g KI. Titrate with $Na_2S_2O_3$ to pale yellow, add 5 ml starch solution, continue titrating to colorless.	0.1 N $Na_2S_2O_3$	Blue-colorless	Cu (oz/gal) = ml × 4.236 × N
Sn	5 ml	100 ml H_2O, 50 ml conc. HCl, 3.0 g iron powder in 500-ml flask. Stopper flask with stopper fitted with a glass tube immersed in a beaker filled with saturated bicarbonate solution. Heat gently till iron dissolves. Cool to room temperature, making sure outlet tube is immersed in bicarbonate solution. Add 10 ml starch solution and bicarbonate during titration.	0.1 N KI-KIO_3	Clear-blue	Sn (oz/gal) = ml × 1.583 × N
NaCN or KCN	5 ml	100 ml H_2O and 10 ml 10KI.	0.1 N $AgNO_3$	Clear-turbid	NaCN (oz/gal) = ml × 2.614 × N KCN (oz/gal) = ml × 3.473 × N
NaOH or KOH	5 ml	25 ml H_2O and 5 ml sulfo-orange.	1.0 N HCl	Orange-yellow	NaOH (oz/gal) = ml × 1.067 × N KOH (oz/gal) = ml × 1.496 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Na_2CO_3 or K_2CO_3	10 ml	100 ml hot H_2O, 35 ml 10% $Ba(NO_3)_2$, allow to settle, filter, wash filter twice with hot H_2O, transfer filter paper and precipitate to a beaker, add 100 ml H_2O and methyl orange.	1.0 N HCl	Orange-pink	Na_2CO_3 (oz/gal) = ml × 0.707 × N K_2CO_3 (oz/gal) = ml × 0.921 × N
$KNaC_4H_4O_6 \cdot 4H_2O$	5 ml	25 ml 20% H_2SO_4, filter, wash flask and filter paper twice each with H_2O, and boil the collected filtrate 5 minutes.	0.1 N $KMnO_4$	Colorless-pink	$KNaC_4H_4O_6 \cdot 4H_2O$ (oz/gal) = ml × 1.250 × N
Cadmium Cyanide					
Cd	2 ml	100 ml H_2O, 10 ml pH 10 buffer, EBT powder, and 15 ml 10% formaldehyde.	0.1 M EDTA	Red-blue	Cd (oz/gal) = ml × 7.493 × M
Total and Free NaCN	5 ml	100 ml H_2O, 15 ml conc. NH_4OH, and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	Total NaCN (oz/gal) = ml × 2.614 × N Free NaCN (oz/gal) = Total NaCN − 1.744 × Cd
NaOH	5 ml	25 ml H_2O and 5 ml sulfo-orange.	1.0 N HCl	Orange-yellow	NaOH (oz/gal) = ml × 1.067 × N
Na_2CO_3	10 ml	100 ml hot H_2O, 35 ml 10% $Ba(NO_3)_2$, allow to settle, filter, wash filter twice with hot H_2O, transfer filter paper and precipitate to a beaker, add 100 ml H_2O and methyl orange.	1.0 N HCl	Orange-pink	Na_2CO_3 (oz/gal) = ml × 0.707 × N
Cadmium Fluoborate					
Cd	2 ml	100 ml H_2O, 10 ml pH 10 buffer, EBT powder, and 15 ml 10% formaldehyde.	0.1 M EDTA	Red-blue	Cd (oz/gal) = ml × 7.493 × M

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
NH_4BF_4	5 ml	50 ml H_2O, boiling chips, 50 ml 20% NaOH in Kjeldahl flask. Attach flask to the distillation apparatus with the collection tube from the condenser immersed in a beaker containing 100 ml saturated H_3BO_3 solution. Boil flask till 20 ml remain in still. Remove beaker and add methyl orange.	0.1 N HCl	Yellow-red	NH_4BF_4 (oz/gal) = ml × 2.795 × N
Cadmium Sulfate					
Cd	2 ml	100 ml H_2O, 10 ml pH 10 buffer, EBT powder, and 15 ml 10% formaldehyde.	0.1 M EDTA	Red-blue	Cd (oz/gal) = ml × 7.493 × M
H_2SO_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	100% H_2SO_4 (oz/gal) = ml × 0.654 × N
Chromium					
$CrO_3(Cr^{6+})$	10 ml of stock	10-ml sample into 500-ml volumetric flask. Pipette 10 ml of stock, add 100 ml H_2O, 2 g ammonium bifluoride, 15 ml conc. HCl, 10 ml 10% KI, and starch solution. (See Table XIII for alternate methods.)	0.1 N $Na_2S_2O_3$	Blue to colorless	CrO_3 (oz/gal) = ml × 22.219 × N
Cr^{3+}	10 ml of stock	10-ml sample into 500 ml volumetric. Pipette 10 ml of stock, add 200 ml H_2O, 0.25 g Na_2O_2, boil gently 30 minutes, maintain volume at 200 ml with H_2O. Cool, add 2 g ammonium bifluoride, 15 ml conc. HCl, 10 ml 10% KI, and starch solution.	0.1 N $Na_2S_2O_3$	Blue to colorless	Cr^{3+} (oz/gal) = (ml × 22.219 × N − Cr^{6+}) × 0.520

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
SO_4	25 ml	100 ml H_2O, 100 ml reducing solution, boil 30 minutes, remove from heat, add 50 ml 10% $Ba(NO_3)_2$, 100 ml hot H_2O. Allow solution to stand for 3–4 hours, heat solution to boiling. Filter in tared Gooch crucible, wash precipitate with hot H_2O, dry in oven at 110°C, cool in desiccator and weigh.			SO_4 (oz/gal) = (weight in grams of precipitate) × 2.195
F	5 ml	100 ml H_2O, 1.0 N NaOH to pH 7.5, using a pH meter previously standardized to pH 7.0. Add 10% $AgNO_3$ solution until the disappearance of the yellow color after settling of the precipitate, filter, wash precipitate, save filtrate. Add Alizarin indicator, 2% HNO_3 till color of solution changes from pink to yellow. Add 3 ml fluoride buffer.	0.1 N $Th(NO_3)_4$	Yellow-pink	F (oz/gal) = ml × 0.507 × N
Copper Cyanide					
CuCN (Method I)	2 ml	15 ml conc. HNO_3, heat to blue color, 100 ml H_2O, conc. NH_4OH to deep blue, heat to 140°F, and add PAN.	0.1 M EDTA	Purple-green	CuCN (oz/gal) = ml × 5.971 × M
CuCN (Method II)	2 ml	100 ml H_2O, 15 ml conc. HNO_3, heat to blue color and disappearance of brown fumes, NH_4OH to deep blue, acetic acid to light blue, 5 g KI. Titrate with $Na_2S_2O_3$ to pale yellow, add 5 ml starch solution, continue titrating to colorless.	0.1 N $Na_2S_2O_3$	Blue-colorless	CuCN (oz/gal) = ml × 5.971 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
$NaCN$ or KCN	5 ml	100 ml H_2O and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	$NaCN$ (oz/gal) = ml × 2.614 × N KCN (oz/gal) = ml × 3.473 × N
$NaOH$ or KOH	5 ml	25 ml H_2O and 5 ml sulfo-orange.	1.0 N HCl	Orange-yellow	$NaOH$ (oz/gal) = ml × 1.067 × N KOH (oz/gal) = ml × 1.496 × N
Na_2CO_3 or K_2CO_3	10 ml	100 ml hot H_2O, 35 ml 10% $Ba(NO_3)_2$, allow to settle, filter, wash filter twice with hot H_2O, transfer filter paper and precipitate to a beaker, add 100 ml H_2O, and methyl orange.	1.0 N HCl	Orange-pink	Na_2CO_3 (oz/gal) = ml × 0.707 × N K_2CO_3, etc K_2CO_3 (oz/gal) = ml × 0.921 × N
$KNaC_4H_4O_6 \cdot 4H_2O$	5 ml	25 ml 20% H_2SO_4, filter, wash flask and filter paper twice each with H_2O, and boil the collected filtrate 5 minutes.	0.1 N $KMnO_4$	Colorless-pink	$KNaC_4H_4O_6 \cdot 4H_2O$ (oz/gal) = ml × 1.250 × N
Copper Fluoborate					
Cu (Method I)	2 ml	100 ml H_2O, conc. NH_4OH to deep blue, heat to 140°F, and add PAN.	0.1 M EDTA	Purple-green	Cu (oz/gal) = ml × 4.236 × M $Cu(BF_4)_2$ (oz/gal) = Cu × 3.73
Cu (Method II)	2 ml	100 ml H_2O, NH_4OH to deep blue, acetic acid to light blue, 5 g KI. Titrate with $Na_2S_2O_3$ to pale yellow, add 5 ml starch solution, continue titrating to colorless.	0.1 N $Na_2S_2O_3$	Blue-colorless	Cu (oz/gal) = ml × 4.236 × N
HBF_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-green	100% HBF_4 (oz/gal) = ml × 1.171 × N
Copper Pyrophosphate					
Cu (Method I)	2 ml	100 ml H_2O conc. NH_4OH to deep blue, heat to 140°F and add PAN.	0.1 M EDTA	Purple-green	Cu (oz/gal) = ml × 4.236 × M

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Cu (Method II)	2 ml	100 ml H_2O, NH_4OH to deep blue, acetic acid to light blue, 5 g KI. Titrate with $Na_2S_2O_3$ to pale yellow, add 5 ml starch solution, continue titrating to colorless.	0.1 N $Na_2S_2O_3$	Blue-colorless	Cu (oz/gal) = ml × 4.236 × N
Total P_2O_7	5 ml	100 ml H_2O, 1.0 N HCl dropwise to pH 3.8 (use pH meter standardized at pH 4.0), back-titrate with 1.0 N NaOH if pH 3.8 is overshot, stir 5 minutes and make sure pH is 3.6–3.8, add 50 ml 20% $ZnSO_4$ (adjusted to pH 3.8) and stir 10 minutes. Titrate slowly with stirring using 1.0 N NaOH to pH 3.8 (note these ml NaOH used for calculation).	1.0 N NaOH		Total P_2O_7 (oz/gal) = ml × 2.32 × N + Cu × 1.37 Ratio = [Total P_2O_7 (oz/gal)]/Cu (oz/gal)
NH_3	10 ml	200 ml H_2O, boiling chips, 50 ml 20% NaOH in Kjeldahl flask. Attach flask to the distillation apparatus with the collection tube from the condenser immersed in a beaker containing 100 ml saturated H_3BO_3 solution. Boil flask and distill over 100 ml. Remove beaker and add methyl orange.	0.1 N HCl	Yellow-red	29% NH_3 (oz/gal) = ml × 0.80 × N
Copper Sulfate					
Cu (Method I)	2 ml	100 ml H_2O, conc. NH_4OH to deep blue, heat to 140°F, and add PAN.	0.1 M EDTA	Purple-green	Cu (oz/gal) = ml × 4.236 × M $CuSO_4 \cdot 5H_2O$ (oz/gal) = Cu × 3.93
Cu (Method II)	2 ml	100 ml H_2O, NH_4OH to deep blue, acetic acid to light blue, 5 g KI. Titrate with $Na_2S_2O_3$ to pale yellow, add 5 ml starch solution, continue titrating to colorless.	0.1 N $Na_2S_2O_3$	Blue-colorless	Cu (oz/gal) = ml × 4.236 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Cu (Method III)		(See Table XIV)			
H_2SO_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-green	100% H_2SO_4 (oz/gal) = ml × 0.654 × N
Cl	50 ml	50 ml H_2O, 25 ml 50% HNO_3, 5 drops 0.1 N $AgNO_3$. Note: For chloride analysis, carbon-treat the solution prior to analysis.	0.01 N $Hg(NO_3)_2$	Turbid-clear	Cl (ppm) = ml × 709.1 × N
Acid Gold					
Au	20 ml	25 ml conc. H_2SO_4, heat to white fumes, cool, add 10 ml 30% H_2O_2, heat to white fumes. Repeat H_2O_2 and heating until Au sponge coagulates and solution clears. Cool, add 100 ml H_2O, heat at 140°F for 5 minutes. Filter through Gooch crucible containing fiberglass filter paper, wash Au sponge with hot H_2O, dry crucible in oven at 110°C, cool in desiccator and weigh.			Au (g/L) = (weight of gold precipitate) × 50.0
Gold Cyanide					
Au	20 ml	Procedure as above for acid gold.			As above for acid gold.
NaCN or KCN	5 ml	100 ml H_2O, 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	NaCN (g/L) = ml × 19.605 × N KCN (g/L) = ml × 26.048 × N
Na_2CO_3 or K_2CO_3	10 ml	100 ml hot H_2O, 35 ml 10% $Ba(NO_3)_2$, allow to settle, filter, wash filter twice with hot H_2O, transfer filter paper and precipitate to a beaker, add 100 ml H_2O, and methyl orange.	1.0 N HCl	Orange-pink	$NaCO_3$ (g/L) = ml × 5.303 × N K_2CO_3 (g/L) + ml × 6.908 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Indium Cyanide					
In	2 ml	100 ml H_2O, 50 ml Rochelle solution, 10 ml pH 10 buffer, heat to 140°F, and add EBT powder.	0.1 M EDTA	Red-blue	In (oz/gal) = ml × 7.655 × M
Total KCN	5 ml	100 ml H_2O, 20 ml 20% NaOH, and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	Total KCN (oz/gal) = ml × 3.473 × N
Free KCN	5 ml	100 ml H_2O and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	Free KCN (oz/gal) = ml × 3.473 × N
KOH	5 ml	25 ml H_2O and 5 ml sulfo-orange.	1.0 N HCl	Orange-yellow	KOH (oz/gal) = ml × 1.496 × N
Indium Fluoborate					
In	2 ml	100 ml H_2O, 50 ml Rochelle solution, 10 ml pH 10 buffer, heat to 140°F, and add EBT powder.	0.1 M EDTA	Red-blue	In (oz/gal) = ml × 7.655 × M
NH_4BF_4	5 ml	50 ml H_2O, boiling chips, 50 ml 20% NaOH in Kjeldahl flask. Attach flask to the distillation apparatus with the collection tube from the condenser immersed in a beaker containing 100 ml saturated H_3BO_3 solution. Boil flask till 20 ml remain in still. Remove beaker and add methyl orange.	0.1 N HCl	Yellow-red	NH_4BF_4 (oz/gal) = ml × 2.795 × N
Iron Chloride					
Fe^{2+}	5 ml	100 ml H_2O, 25 ml 20% $ZnSO_4$, and 50 ml 10% H_2SO_4.	0.1 N $KMnO_4$	Colorless-pink	Fe^{2+} (oz/gal) = ml × 1.489 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Total Fe	5 ml	100 ml H_2O, 5 g Cd flakes, boil 5 minutes, cool and decant liquid into 500-ml flask, wash Cd residue with H_2O and add to flask, add 25 ml 20% $ZnSO_4$, and 50 ml 10% H_2SO_4.	0.1 $KMNO_4$	Colorless-pink	Total Fe (oz/gal) = ml × 1.489 × N Fe^{3+} (oz/gal) = Total Fe − Fe^{2+}
HCl	25 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	36% HCl (oz/gal) = ml × 0.540 × N
Iron Fluoborate					
Fe^{2+}	5 ml	100 ml H_2O, 25 ml 20% $ZnSO_4$, and 50 ml 10% H_2SO_4.	0.1 $KMnO_4$	Colorless-pink	Fe^{2+} (oz/gal) = ml × 1.489 × N
Total Fe	5 ml	100 ml H_2O, 5 g Cd flakes, boil 5 minutes, cool and decant liquid into 500-ml flask, wash Cd residue with H_2O and add to flask, add 25 ml 20% $ZnSO_4$, and 50 ml 10% H_2SO_4.	0.1 N $KMnO_4$	Colorless-pink	Total Fe (oz/gal) = ml × 1.489 × N Fe^{3+} (oz/gal) = Total Fe − Fe^{2+}
NaCl	5 ml	100 ml H_2O, 5 ml 30% H_2O_2, boil for 10 minutes, filter, wash precipitate with hot H_2O, and add K_2CrO_4 to filtrate.	0.1 N $AgNO_3$	Yellow-red	NaCl (oz/gal) = ml × 1.558 × N
Lead Fluoborate					
Pb	1 ml	100 ml H_2O, 25 ml Rochelle solution, 20 ml conc. NH_4OH, and EBT solution.	0.1 M EDTA	Red-blue	Pb (oz/gal) = ml × 27.625 × M
HBF_4	10 ml	100 ml H_2O.	1.0 N NaOH	Clear-turbid	100% HBF_4 (oz/gal) = ml × 1.171 × N
Black Nickel					
Zn	2 ml	100 ml H_2O, 10 ml pH 10 buffer, EBT powder, and 15 ml 10% formaldehyde.	0.1 M EDTA	Red-blue	Zn (oz/gal) = ml × 4.358 × M

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Ni	2 ml	100 ml H_2O, 10 ml conc. NH_4OH, and murexide powder.	0.1 M EDTA	Orange-purple	Ni (oz/gal) = (ml EDTA for Ni − ml EDTA for Zn) × 3.914 × M
NaSCN	10 ml	100 ml H_2O, 15 ml 20% H_2SO_4, and FAS indicator.	0.1 N $AgNO_3$	Red-colorless	NaSCN (oz/gal) = ml × 1.081 × N
Nickel Fluoborate					
Ni	2 ml	100 ml H_2O, 10 ml conc. NH_4OH, and murexide powder.	0.1 M EDTA	Orange-purple	Ni (oz/gal) = ml × 3.914 × M
H_3BO_3	10 ml	25 ml H_2O, 5.0 g mannitol, and bromocresol purple.	1.0 N NaOH	Green-purple	H_3BO_3 (oz/gal) = ml × 0.824 × N
Nickel Strike					
Ni	2 ml	100 ml H_2O, 20 ml conc. NH_4OH, and murexide powder.	0.1 M EDTA	Orange-purple	Ni (oz/gal) = ml × 3.914 × M
HCl	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	36% HCl (fl oz/gal) = ml × 1.115 × N
Nickel Sulfamate					
Ni	2 ml	100 ml H_2O, 20 ml conc. NH_4OH, and murexide powder.	0.1 M EDTA	Orange-purple	Ni (oz/gal) = ml × 3.914 × M
$NiBr_2$	5 ml	100 ml H_2O and K_2CrO_4.	0.1 N $AgNO_3$	Yellow/green-red	$NiBr_2$ (oz/gal) = ml × 2.914 × N
$NiCl_2{\cdot}6H_2O$	20 ml	100 ml H_2O and K_2CrO_4.	0.1 N $AgNO_3$	Yellow/green-red	$NiCl_2{\cdot}6H_2O$ (oz/gal) = ml × 0.792 × N
H_3BO_3	10 ml	25 ml H_2O, 5.0 g mannitol, and bromocresol purple.	1.0 N NaOH	Green-purple	H_3BO_3 (oz/gal) = ml × 0.824 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
SO_4	10 ml	100 ml H_2O, 5 ml 50% HCl, 25 ml $Ba(NO_3)_2$, allow solution to stand 4 hours, filter in tared Gooch crucible, wash precipitate with H_2O, dry in oven at 110°C, cool in desiccator, and weigh.			SO_4 (oz/gal) = (weight in grams of precipitate) × 5.488
Watts Nickel					
Ni	2 ml	100 ml H_2O, 20 ml conc. NH_4OH, and murexide powder.	0.1 M EDTA	Orange-purple	Ni (oz/gal) = ml × 3.914 × M
$NiCl_2{\cdot}6H_2O$	1 ml	100 ml H_2O, 1 ml K_2CrO_4 (if pH is below 4.0, add 1.0 g $CaCO_3$).	0.1 N $AgNO_3$	Yellow/green-red	$NiCl_2{\cdot}6H_2O$ (oz/gal) = ml × 15.847 × N $NiSO_4{\cdot}6H_2O$ (oz/gal) = 4.5 (Ni − 0.247 × $NiCl_2{\cdot}6H_2O$)
H_3BO_3	10 ml	25 ml H_2O, 5.0 g mannitol, and bromocresol purple.	1.0 N NaOH	Green-purple	H_3BO_3 (oz/gal) = ml × 0.824 × N
Nickel-Iron					
Ni	2 ml	100 ml H_2O, 20 ml conc. NH_4OH, and murexide powder.	0.1 M EDTA	Orange-purple	Ni (oz/gal) = ml × 3.914 × M
Fe^{2+}	5 ml	100 ml H_2O, 25 ml 20% $ZnSO_4$, and 50 ml 10% H_2SO_4.	0.1 N $KMnO_4$	Colorless-pink	Fe^{2+} (oz/gal) = ml × 1.489 × N
Total Fe	5 ml	100 ml H_2O, 5 g Cd flakes, boil 5 minutes, cool and decant liquid into 500-ml flask, wash Cd residue with H_2O and add to flask, add 25 ml 20% $ZnSO_4$, and 50 ml 10% H_2SO_4.	0.1 $KMNO_4$	Colorless-pink	Total Fe (oz/gal) = ml × 1.489 × N Fe^{3+} (oz/gal) = Total Fe − Fe^{2+}
H_3BO_3	10 ml	25 ml H_2O, 5.0 g mannitol, and bromocresol purple.	1.0 N NaOH	Green-purple	H_3BO_3 (oz/gal) = ml × 0.824 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Palladium Pd	10 ml	10 ml conc. HNO_3, heat until syrupy, 10 ml conc. HNO_3, heat to onset of boiling. Add 250 ml H_2O, cool, slowly add 40 ml dimethylglyoxime solution, allow solution to stand at least 2 hours, filter through No. 3 porosity tared crucible, wash precipitate with H_2O. Dry in oven at 110°C, cool in desiccator, and weigh.			Pd (g/L) = (weight in grams of precipitate) × 31.67
Platinum Pt	10 ml	10 ml conc. HCl, heat until syrupy, 100 ml H_2O, 5 g sodium acetate, 1 ml conc. formic acid, heat at 140°F for 5 hours, filter, wash precipitate with hot H_2O. Place filter paper and Pt precipitate in tared porcelain crucible, dry slowly with Bunsen burner, char filter paper, dry Pt precipitate at high temperature for 30 minutes. Cool in desiccator and weigh.			Pt (g/L) = (weight in grams of precipitate) × 100.0
Rhodium Rh	25 ml	2 g Mg turnings, conc. HCl dropwise. When all Mg dissolves, add 0.5 g Mg turnings and HCl dropwise to ensure complete precipitation of Rh. Filter solution in tared Gooch crucible containing fiberglass filter paper, wash precipitate with hot H_2O, dry in oven at 110°C, cool in desiccator and weigh.			Rh (g/L) = (weight in grams of precipitate) × 40.0
H_2SO_4 or H_3PO_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	100% H_2SO_4 (g/L) = ml × 4.904 × N 100% H_3PO_4 (g/L) = ml × 9.800 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Ruthenium					
Ruthenium cannot be easily determined by volumetric or gravimetric methods. It is usually determined by emission spectroscopy and its analysis should be referred to a competent laboratory.					
Silver Cyanide					
Ag	5 ml	15 ml conc. H_2SO_4, 5 ml conc. HNO_3, heat until the disappearance of orange fumes, cool, add 100 ml cold H_2O, and FAS indicator.	0.1 N KSCN	Colorless-red	Ag (oz/gal) = ml × 2.877 × N AgCN (oz/gal) = Ag × 1.241
NaCN or KCN	5 ml	100 ml H_2O and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	NaCN (oz/gal) = ml × 2.614 × N KCN (oz/gal) = ml × 3.473 × N
Na_2CO_3 or K_2CO_3	10 ml	100 ml hot H_2O, 35 ml 10% $Ba(NO_3)_2$ allow to settle, filter, wash filter twice with hot H_2O, transfer filter paper and precipitate to a beaker, add 100 ml H_2O and methyl orange.	1.0 N HCl	Orange-pink	Na_2CO_3 (oz/gal) = ml × 0.707 × N K_2CO_3 (oz/gal) = ml × 0.921 × N
Tin Fluoborate					
Sn^{2+}	2 ml	100 ml H_2O, 25 ml 50% HCl, 10 ml starch solution, add bicarbonate during titration.	0.1 N KI-KIO_3	Colorless-blue	Sn^{2+} (oz/gal) = ml × 3.956 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents - (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Sn^{4+}	2 ml	In 500-ml flask add sample, 100 ml conc. HCl, 2 drops $SbCl_3$ solution. Add 180 ml H_2O, 5-in. folded "U"-shaped nickel strip and 5.0 g reduced iron powder. Stopper flask with rubber stopper fitted with ¼-in. glass tube immersed into a saturated $NaHCO_3$ solution. Heat solution on hot plate to boil for 20 minutes and then place in cooling tank and allow to cool to room temperature. Make sure glass outlet tube is immersed in the $NaHCO_3$. Remove stopper and add starch solution.	0.1 N KI-KIO_3	Colorless-blue	Sn^{4+} (oz/gal) = ml × 3.956 × N − Sn^{2+}
HBF_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Clear-turbid	100% HBF_4 (oz/gal) = ml × 1.171 × N
Free H_3BO_3	10 ml	100 ml H_2O, 10 ml Na_2SO_4 solution. Titrate to pH 7.0, using a pH meter previously standardized to pH 7.0. Add 5 g mannitol, titrate from pH 7.0 to pH 8.0 (ml NaOH required for this step are used for the calculation).	1.0 N NaOH		H_3BO_3 (oz/gal) = ml × 0.824 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Tin Stannate					
$K_2SnO_3 \cdot 3H_2O$ $Na_2SnO_3 \cdot 3H_2O$	5 ml	100 ml H_2O, 50 ml conc. HCl, 3.0 g iron powder in 500-ml flask. Stopper flask with stopper fitted with a glass tube immersed in a beaker filled with saturated bicarbonate solution. Heat gently till iron dissolves. Cool to room temperature, making sure outlet tube is immersed in bicarbonate solution. Add 10 ml starch solution and bicarbonate during titration.	0.1 N KI-KIO_3	Colorless-blue	$K_2SnO_3 \cdot 3H_2O$ (oz/gal) = ml × 3.986 × N $Na_2SnO_3 \cdot 3H_2O$ (oz/gal) = ml × 3.556 × N
KOH NaOH	5 ml	25 ml H_2O and 5 ml sulfo-orange	1.0 N HCl	Orange-yellow	KOH (oz/gal) = ml × 1.496 × N NaOH (oz/gal) = ml × 1.067 × N
Tin Sulfate					
$SnSO_4$	5 ml	100 ml H_2O, 25 ml 50% HCl, 10 ml starch solution, add bicarbonate during titration.	0.1 N KI-KIO_3	Colorless-blue	$SnSO_4$ (oz/gal) = ml × 2.863 × N Sn^{2+} (oz/gal) = $SnSO_4$ × 0.553
Sn^{4+}	2 ml	In 500-ml flask add sample, 100 ml conc. HCl, 2 drops $SbCl_3$ solution. Add 180 ml H_2O, 5-in. folded "U"-shaped nickel strip and 5.0 g reduced iron powder. Stopper flask with rubber stopper fitted with ¼-in. glass tube immersed into a saturated $NaHCO_3$ solution. Heat solution on hot-plate to boil for 20 minutes and then place in cooling tank and allow to cool to room temperature. Make sure glass outlet tube is immersed in the $NaHCO_3$. Remove stopper and add starch solution.	0.1 N KI-KIO_3	Colorless-blue	Sn^{4+} (oz/gal) = ml × 3.956 × N − Sn^{2+}

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
H_2SO_4	10 ml	100 ml H_2O, 25 ml ammonium oxalate solution, and methyl orange.	1.0 N NaOH	Red-orange/yellow	100% H_2SO_4 (oz/gal) = ml × 0.654 % v H_2SO_4 = ml × 0.279 × N
Tin-Lead Fluoborate					
Sn^{2+}	100 ml	H_2O, 25 ml 50% HCl, 10 ml starch solution, add bicarbonate during titration	0.1 N KI-KIO_3	Colorless-blue	Sn^{2+} (oz/gal) = ml × 3.956 × N
Sn^{4+}	2 ml	In 500-ml flask add sample, 100 ml conc. HCl, 2 drops $SbCl_3$ solution. Add 180 ml H_2O, 5-in. folded "U"-shaped nickel strip and 5.0 g reduced iron powder. Stopper flask with rubber stopper fitted with ¼-in. glass tube immersed into a saturated $NaHCO_3$ solution. Heat solution on hot-plate to boil for 20 minutes and then place in cooling tank and allow to cool to room temperature. Make sure glass outlet tube is immersed in the $NaHCO_3$. Remove stopper and add starch solution.	0.1 N KI-KIO_3	Colorless-blue	Sn^{4+} (oz/gal) = ml × 3.956 × N − Sn^{2+}
Pb	2 ml	5 ml conc. HNO_3, heat till syrupy, cool and add: 25 ml Rochelle solution, 15 ml conc. NH_4OH, 15 ml 10% NaCN and EBT solution.	0.1 M EDTA	Red-blue	Pb (oz/gal) = ml × 13.813 × M
HBF_4	10 ml	100 ml H_2O.	1.0 N NaOH	Clear-turbid	100% HBF_4 (oz/gal) = ml × 1.171 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Free H_3BO_3	10 ml	100 ml H_2O, 10 ml Na_2SO_4 solution. Titrate to pH 7.0, using a pH meter previously standardized to pH 7.0. Add 5 g mannitol, titrate from pH 7.0 to pH 8.0 (ml NaOH required for this step are used for the calculation).	1.0 N NaOH		H_3BO_3 (oz/gal) = ml × 0.824 × N
Tin-Lead Methane Sulfonate					
Sn^{+2}	5 ml	100 ml H_2O, 25 ml 50% HCl, 10 ml starch solution, add bicarbonate during titration.	0.1 N KI-KIO_3	Colorless blue	Sn^{2+} (g/L) = ml × 11.869 × N
Sn^{4+}	5 ml	In 500-ml flask add sample, 100 ml conc. HCl, 2 drops $SbCl_3$ solution. Add 180 ml H_2O, folded "U"-shaped nickel strip and 5.0 g reduced iron powder. Stopper flask with rubber stopper fitted with ¼-in. glass tube immersed into a saturated $NaHCO_3$ solution. Heat solution on hot-plate to boil for 20 minutes and then place in cooling tank and allow to cool to room temperature. Make sure glass outlet tube is immersed in the $NaHCO_3$. Remove stopper and add starch solution.	0.1 N KI-KIO_3	Colorless-blue	Sn^{4+} (g/L) = ml × 11.869 × N (Sn^{2+})
Pb	25 ml	75 ml H_2O, 3 ml H_2O_2, 50 ml Rochelle solution, 25 ml pH 10 buffer, EBT solution, 15 ml 10% formaldehyde.	0.1 M EDTA	Red-blue	Pb (g/L) = ml × 8.288 × M
Methane sulfonic acid (MSA)	10 ml	100 ml H_2O, phenolphthalein.	1.0 N NaOH	Colorless-pink	100% MSA (g/L) = ml × 9.61 × N

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Tin-Nickel					
Sn	2 ml	100 ml H_2O, 25 ml 50% HCl, 10 ml starch solution, add bicarbonate during titration.	0.1 N KI-KIO_3	Clear blue	Sn (oz/gal) = ml × 3.956 × N
Ni	2 ml	25 ml H_2O, 1 ml 30% H_2O_2, heat gently to boil, cool, add 10 ml tartaric acid solution. Neutralize with conc. NH_4OH to a blue color, add 20 ml pH 10 buffer, 150 ml H_2O, and murexide powder.	0.1 M EDTA	Orange-purple	Ni (oz/gal) = ml × 3.914 × M
NH_4HF_2	10 ml	200 ml H_2O, boiling chips, 50 ml 20% NaOH in Kjeldahl flask. Attach flask to the distillation apparatus with the collection tube from the condenser immersed in a beaker containing 100 ml saturated H_3BO_3 solution. Boil flask and distill over 100 ml. Remove beaker from collection tube before removing heat source. Add methyl orange.	0.1 N HCl	Yellow-red	NH_4HF_2 (oz/gal) = ml × 0.761 × N
Zinc Chloride					
Zn	2 ml	100 ml H_2O, 10 ml pH 10 buffer, EBT powder, and 15 ml 10% formaldehyde.	0.1 M EDTA	Red-blue	Zn (oz/gal) = ml × 4.358 × M
Cl	1 ml	100 ml H_2O, 1 ml K_2CrO_4.	0.1 N $AgNO_3$	Yellow-red	Cl (oz/gal) = ml × 4.727 × N
Zinc Cyanide					
Zn	2 ml	100 ml H_2O, 10 ml pH 10 buffer, EBT powder, and 15 ml 10% formaldehyde.	0.1 M EDTA	Red-blue	Zn (oz/gal) = ml × 4.358 × M

Table VIII. Test Methods for Electroplating Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Total NaCN	1 ml	100 ml H_2O, 20 ml 20% NaOH, and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	Total NaCN (oz/gal) = ml × 13.069 × N
NaOH	5 ml	25 ml H_2O, 5 ml sulfo-orange.	1.0 N HCl	Orange-yellow	NaOH (oz/gal) = ml × 1.067 × N
Na_2CO_3	10 ml	100 ml hot H_2O, 35 ml 10% $Ba(NO_3)_2$, allow to settle, filter, wash filter twice with hot H_2O, transfer filter paper and precipitate to a beaker, add 100 ml H_2O, and methyl orange.	1.0 N HCl	Orange-pink	Na_2CO_3 (oz/gal) = ml × 0.707 × N

EDTA, ethylene diamine tetra acetic acid; PAN, peroxy acetyl nitrate.
[a]Use deionized or distilled water for all solutions.

Table IX. Test Methods for Electroless Plating Solutions

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Copper					
Cu	20 ml	100 ml H_2O,[a] conc. NH_4OH to deep blue, heat to 140°F, and add peroxyacetal nitrate.	0.1 M EDTA	Purple-green	Cu (g/L) = ml × 3.177 × M
NaOH	5 ml	150 ml H_2O. Titrate to pH 10.5, using a pH meter previously standardized to pH 10.0.	0.1 N HCl		NaOH (g/L) = ml × 8.0 × N
HCHO	5 ml	100 ml H_2O. Adjust pH to 9.0, using a pH meter previously standardized to pH 10.0. Add 25 ml sodium sulfite solution, stir 1 minute. Titrate to pH 9.0 (these ml are used for the calculation).	0.1 N HCl		HCHO (g/l) = ml × 16.232 × N
Nickel					
Ni	5 ml	100 ml H_2O, 20 ml conc. NH_4OH, and murexide powder.	0.1 M EDTA	Orange-purple	Ni (oz/gal) = ml × 1.566 × M
$NaH_2PO_2 \cdot H_2O$	5 ml	Use glass-stoppered iodine flask. Add 5 ml conc. H_2SO_4 and 50 ml 0.1 N iodine solution. Swirl to mix, stopper flask, and place in dark for 30 minutes, then add starch solution.	0.1 N $Na_2S_2O_3$	Blue-colorless	$NaH_2PO_2 \cdot H_2O$ (oz/gal) = (ml I_2 × N-I_2 − ml $Na_2S_2O_3$ × N-$Na_2S_2O_3$) × 1.413
Tin					
Sn^{2+}	2 ml	100 ml H_2O, 25 ml 50% HCl, 10 ml starch solution, add bicarbonate during titration.	0.1 N KI-KIO_3	Clear-blue	Sn (oz/gal) = ml × 3.956 × N

EDTA, ethylene diamine tetra acetic acid.

[a] Use deionized or distilled water for all solutions.

Table X. Test Methods for Anodizing Solutions

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
Chromic					
CrO_3[a]	10 ml of stock	10 ml sample into 500 ml volumetric. Pipette 10 ml of stock, add 100 ml H_2O,[b] 2 g ammonium bifluoride, 15 ml conc. HCl, 15 ml 10% KI, and starch solution.	0.1 N $Na_2S_2O_3$	Blue-colorless	CrO_3 (oz/gal) = ml × 22.219 × N
Free CrO_3	25 ml	100 ml H_2O. Titrate to pH 3.05, using a pH meter previously standardized to pH 4.0.	1.0 N NaOH	Colorless–pink	Free CrO_3 (oz/gal) = ml × 0.533 × N
Sulfuric					
Total H_2SO_4	5 ml	100 ml H_2O and phenolphthalein.	1.0 N NaOH	Colorless-pink	Total H_2SO_4 (oz/gal) = ml × 1.308 × N
Free H_2SO_4	5 ml	100 ml H_2O, 10 ml KF solution, and phenolphthalein.	1.0 N NaOH	Colorless-pink	Free H_2SO_4 (oz/gal) = ml × 1.308 × N
Al					Al (oz/gal) = (ml NaOH for Total H_2SO_4 − ml NaOH for free H_2SO_4) × 0.240 × N

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[a] See also alternate method in Fig. 2.

[b] Use deionized or distilled water for all solutions.

Table XI. Test Methods for Acid Dips and Electropolishing Solutions

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
$HC_2H_3O_2$	10 ml	100 ml H_2O^a and phenolphthalein.	1.0 N NaOH	Colorless-pink	% wt $HC_2H_3O_2$ (100%) = (ml × 0.6005 × N)/s.g. solution
$H_3C_6H_5O_7{\cdot}H_2O$ (Citric acid)	10 ml	100 ml H_2O and phenolphthalein.	1.0 N NaOH	Colorless-pink	% wt $H_3C_6H_5O_7{\cdot}H_2O$ = (ml × 0.7005 × N)/s.g. solution
HBF_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	% wt HBF_4 (100%) = (ml × 0.8781 × N)/s.g. solution
HCl	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	% wt HCl (100%) = (ml × 0.3646 × N)/s.g. solution
HF	2 g	100 ml H_2O and phenolphthalein. (Note: use plastic labware.)	1.0 N NaOH	Colorless-pink	% wt HF (100%) = (ml × 2.001 × N)/wt
HNO_3	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	% wt HNO_3 (100%) = (ml × 0.6301 × N)/s.g. solution
H_3PO_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	% wt H_3PO_4 (100%) = (ml × 0.9800 × N)/s.g. solution
H_2SO_4	10 ml	100 ml H_2O and methyl orange	1.0 N NaOH	Red-yellow/green	% wt H_2SO_4 (100%) = (ml × 0.4904 × N)/s.g. solution
HNO_3 + HF	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	A ml
	1 ml	100 ml H_2O, Alizarin, 1.0 N NaOH to pink, 2% HNO_3 dropwise from pink to yellow, 3 ml fluoride buffer.	0.1 N $Th(NO_3)_4$	Yellow-pink	B ml % wt HNO_3 (100%) = [(A ml × N − 10 × B ml × N) × 0.6301]/s.g. solution % wt HF (100%) = (B ml × 20.006 × N)/s.g. solution
H_3PO_4 + H_2SO_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	A ml
		Add phenolphthalein to the solution above.	1.0 N NaOH	Purple-red	B ml % wt H_2SO_4 (100%) = [(A ml − B ml) × 0.4904 × N]/s.g. solution % wt H_3PO_4 (100%) = (B ml × 0.9800 × N)/s.g. solution
H_2SO_4 + H_2O_2 H_2SO_4	10 ml	100 ml H_2O and methyl orange.	1.0 N NaOH	Red-yellow/green	% wt H_2SO_4 (100%) = (ml × 0.4904 × N)/s.g. solution

Table XI. Test Methods for Acid Dips and Electropolishing Solutions *(cont.)*

Bath	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
H_2O_2	2 ml	100 ml H_2O and 25 ml 20% H_2SO_4.	0.1 N $KMnO_4$	Colorless-pink	% wt H_2O_2 (100%) = (ml × 28.345 × N)/s.g. solution
$CrO_3 + H_2SO_4$ CrO_3	10 ml of stock	10-ml sample into 500 ml volumetric flask. Pipette 10 ml of stock, add 100 ml H_2O, 2 g ammonium bifluoride, 15 ml conc. HCl, 10 ml 10% KI, and starch solution.	0.1 N $Na_2S_2O_3$	Blue-colorless	CrO_3 (oz/gal) = ml × 22.219 × N
H_2SO_4	25 ml	100 ml H_2O, 100 ml reducing solution, boil 30 minutes, remove from heat, add 50 ml 10% $Ba(NO_3)_2$, 100 ml hot H_2O. Allow solution to stand for 3–4 hours, heat solution to boiling. Filter in tared Gooch crucible, wash precipitate with hot H_2O, dry in oven at 110°C, cool in desiccator, and weigh.			100% H_2SO_4 (oz/gal) = (weight in grams of precipitate) × 2.241

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[a] Use deionized or distilled water for all solutions.

Table XII. Test Methods for Alkaline Cleaners

Solution	Sample Size	Reagents (To be added in order listed)	Titrant	Color Change	Calculations (ml, N, M-titrant)
Na_2O	25 ml	100 ml H_2O^a and methyl orange.	1.0 N HCl	Yellow-orange/red	Na_2O (oz/gal) = ml × 0.165 × N
Na_2CO_3 + NaOH	10 ml	100 ml H_2O and sulfo orange.	1.0 N HCl	Orange-yellow	B ml
	10 ml	100 ml H_2O and methyl orange.	1.0 N HCl	Yellow-orange/red	A ml Na_2CO_3 (oz/gal) = (A ml − B ml)× 0.707 × N NaOH (oz/gal) = B ml × 0.533 × N
NaOH + NaCN	10 ml	100 ml H_2O and sulfo orange.	1.0 N HCl	Orange-yellow	NaOH (oz/gal) = ml × 0.533 × N
NaOH					
NaCN	10 ml	100 ml H_2O and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	NaCN (oz/gal) = ml × 1.307 × N
Na_2CO_3 + NaCN	10 ml	100 ml H_2O and methyl orange.	1.0 N HCl	Yellow-orange/red	A ml
	10 ml	100 ml H_2O and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	B ml NaCN (oz/gal) = B ml × 1.307 × N Na_2CO_3 (oz/gal) = (A ml × N − B ml × N) × 0.707
Na_2CO_3 + Na_3PO_4	10 ml	150 ml H_2O and methyl orange.	1.0 N HCl	Yellow-orange/red	A ml
		Boil above solution 5 minutes, cool, and add phenolphthalein.	1.0 N NaOH	Colorless-pink	B ml Na_3PO_4 (oz/gal) = B ml × 2.186× N Na_2CO_3 (oz/gal) = (A ml × N − 2 × B ml × N) × 0.707
Na_3PO_4 + NaCN + $Na_2SiO_3{\cdot}5H_2O$	10 ml	150 ml H_2O and methyl orange.	1.0 N HCl	Yellow-orange/red	A ml
		Boil above solution 5 minutes, cool, and add phenolphthalein.	1.0 N NaOH	Colorless-pink	B ml
	10 ml	100 ml H_2O and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	C ml Na_3PO_4 (oz/gal) = B ml × 2.186× N NaCN (oz/gal) = C ml × 1.307 × N $Na_2SiO_3{\cdot}5H_2O$ (oz/gal) = (A ml × N − 2 × B ml × N − C ml × N) × 1.414

Table XII. Test Methods for Alkaline Cleaners *(cont.)*

Solution	*Sample Size*	*Reagents (To be added in order listed)*	*Titrant*	*Color Change*	*Calculations (ml, N, M-titrant)*
$NaOH + Na_2CO_3 + Na_3PO_4$	10 ml	150 ml H_2O and methyl orange.	1.0 N HCl	Yellow-orange/red	A ml
		Boil above solution 5 minutes, cool, and add phenolphthalein. 1.0	1.0 NaOH	Colorless-pink	B ml
	10 ml	100 ml H_2O and phenolphthalein.	1.0 N HCl	Pink-colorless	C ml NaOH (oz/gal) = (2 × C ml − A ml) × 0.533 × N Na_2CO_3 (oz/gal) = (A ml × N − B ml × N − C ml × N) × 1.414 Na_3PO_4 (oz/gal) = B ml × 2.186 × N
$NaOH + Na_3PO_4 + NaCN$	10 ml	150 ml H_2O and methyl orange.	1.0 N HCl	Yellow-orange/red	A ml
		Boil above solution 5 minutes, cool, and add phenolphthalein. 1.0	1.0 NaOH	Colorless-pink	B ml
	10 ml	100 ml H_2O and 10 ml 10% KI.	0.1 N $AgNO_3$	Clear-turbid	C ml Na_3PO_4 (oz/gal) = B ml × 2.186 × N NaCN (oz/gal) = C ml × 1.307 × N NaOH (oz/gal) = A ml × N − 2 × B ml × N − C ml × N) × 0.533

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[a] Use deionized or distilled water for all solutions.

Table XIII. Alternate Method for Chromic Acid

Degrees Baumé	*Oz/gal-CrO_3*	*Degrees Baumé*	*Oz/gal-CrO_3*
1.50	2.1	19.00	29.0
2.00	2.8	19.50	29.8
2.50	3.4	20.00	30.6
3.00	4.1	20.50	31.5
3.50	4.8	21.00	32.4
4.00	5.5	21.50	33.3
4.50	6.2	22.00	34.2
5.00	6.8	22.50	35.1
5.50	7.5	23.00	36.0
6.00	8.2	23.50	37.1
6.50	8.9	24.00	38.2
7.00	9.7	24.50	39.1
7.50	10.4	25.00	40.0
8.00	11.1	25.50	40.9
8.50	11.9	26.00	41.9
9.00	12.6	26.50	42.9
9.50	13.4	27.00	44.0
10.00	14.2	27.50	45.0
10.50	15.0	28.00	46.0
11.00	15.8	28.50	47.1
11.50	16.5	29.00	48.2
12.00	17.3	29.50	49.2
12.50	18.2	30.00	50.2
13.00	19.1	30.50	51.5
13.50	19.8	31.00	52.7
14.00	20.4	31.50	54.0
14.50	21.2	32.00	55.2
15.00	22.0	32.50	56.3
15.50	22.9	33.00	57.5
16.00	23.7	33.50	58.7
16.50	24.5	34.00	60.0
17.00	25.4	34.50	61.2
17.50	26.3	35.00	62.3
18.00	27.2	35.50	63.5
18.50	28.1	36.00	64.8

Procedure: 1. Cool the solution to room temperature after testing.
2. Determine the density of the solution with a Baumé hydrometer.
3. Read the oz/gal of chromic acid (CrO_3) corresponding to this density.

Table XIV. Alternate Method for Copper Sulfate

Baumé	*Copper Sulfate + Sulfuric Acid (oz/gal)*	*Baumé*	*Copper Sulfate + Sulfuric Acid (oz/gal)*
1.5	2.8	14.5	24.7
2.0	3.5	15.0	25.7
2.5	4.3	15.5	26.8
3.0	5.1	16.0	27.8
3.5	5.9	16.5	28.8
4.0	6.7	17.0	29.8
4.5	7.4	17.5	30.8
5.0	8.2	18.0	31.8
5.5	9.0	18.5	32.8
6.0	9.8	19.0	33.8
6.5	10.6	19.5	34.9
7.0	11.5	20.0	35.9
7.5	12.3	20.5	37.0
8.0	13.1	21.0	38.1
8.5	13.9	21.5	39.2
9.0	14.8	22.0	40.4
9.5	15.7	22.5	41.6
10.0	16.6	23.0	42.8
10.5	17.5	23.5	43.9
11.0	18.3	24.0	45.0
11.5	19.2	24.5	46.1
12.0	20.0	25.0	47.3
12.5	21.0	25.5	48.5
13.0	21.9	26.0	49.7
13.5	22.9	26.5	51.0
14.0	23.8	27.0	52.3

Copper sulfate can be determined by taking the Baumé reading. This gives the combined copper sulfate plus sulfuric acid. Subtraction of the ounces of acid leaves the ounces of copper sulfate.

This method of obtaining the concentration of copper sulfate plus sulfuric acid is not accurate if other ingredients such as aluminum sulfate are present or if the solution is contaminated with iron.

THICKNESS TESTING

by Norbert Sajdera

Kocour Co., Chicago

Coatings are applied to base materials to provide properties not inherent in the base. These include, but are not limited to, corrosion protection, wear resistance, conductivity, color, reflectivity, and solderability.

The amount of coating applied is critical to the final product's utility and cost. The determination of the amount of coating is, therefore, important in appraising its utility and assessing its cost.

Thickness is the most commonly used word to describe the amount of coating. A few of the methods used measure the linear depth of the coating directly. These include the micrometer, with variations using styluses attached to sensitive mechanical and electronic amplifiers, and the microscope, with various methods to expose the coating layers for measurement.

More commonly, gauges estimating the weight per measured area are used. The thickness is then calculated using the following equation:

$$T = m \times 10/A \times d, \tag{1}$$

where T = thickness (μm), m = mass of coating (mg), A = area tested (cm^2), and d = density (g/cm^3).

The instruments using the weight per unit area as the basis for their measurements are beta backscatter, coulometric, and X-ray.

The magnetic and eddy-current methods compare the magnetic and electrical properties of the base and coating materials to calibrated standards with similar properties. The drop test is based on the rate of attack of certain chemical solutions. With such a diversity of methods, it is useful to use the summary in Table I to help choose a measuring system for a particular requirement. The gravimetric, microscopic, and X-ray are not included in Table I, because they apply to almost all of the coating combinations listed. A convenient conversion table for different systems of units is given in Table II.

BETA BACKSCATTER

If a stream of beta particles is directed at matter, it will collide with the atoms in the matter. This results in a reduction of speed and a change in direction of the particles. Those particles that leave the matter through the same surface from which they entered are said to be backscattered. The number of particles backscattered is proportional to the number of atoms per unit area and, therefore, to the atomic weight. The penetration depth of the beta rays is dependent on the energy level of the radioisotope used as their source.

The backscatter can be measured with a Geiger-Müller counter placed in its path. In a measuring system, a radioisotope is placed between the Geiger-Müller counter and the coating to be measured. A stream of particles is directed from the isotope through an aperture and then to the coating. The backscatter radiates back through this stream, passes the radioisotope, and then is measured with the Geiger-Müller counter.

The isotope is chosen on the basis of its maximum energy and half-life. As the thickness of the deposit increases, the energy needed to penetrate the deposit is increased. Metals with larger atomic numbers require higher energies for the same thickness.

As particles are emitted by the source, the number of active particles remaining is reduced. The half-life of an isotope is the time necessary to reduce the activity of the source by one half. As the activity decreases, the instrument requires recalibration for the new activity level.

Table I. Applicability of Coating Thickness Measuring Methods

Substrate	*Copper*	*Nickel*	*Chromium*	*Autocatalytic Nickel*	*Zinc*	*Cadmium*	*Gold*	*Palladium*	*Rhodium*	*Silver*	*Tin*	*Lead*	*Tin-Lead Alloys*	*Nonmetals*	*Vitreous and Porcelain Enamels*
Magnetic steel (including corrosion-resisting steel)	CM	CM[a]	CM	C[b]M[a]	CM	BCM	BM	BM	BM	BCM	BCM	BCM	B[c]C[c]M	BM	M
Nonmagnetic stainless steels	CE[d]	CM[a]	C	C[b]	C	BC	B	B	B	BCE[d]	BC	BC	B[c]C[c]	BE	E
Copper and alloys	C only on brass and Cu-Be	CM[a]	C	C[b]	C	BC	B	B	B	BC	BC	BC	B[c]C[c]	BE	E
Zinc and alloys	C	M[a]	—	—	—	B	B	B	B	B	B	B	B[c]	BE	—
Aluminum and alloys	BC	BCM[a]	BC	BC[b]E[a,b]	BC	BC	B	B	B	BC	BC	BC	B[c]C[c]	E	E
Magnesium and alloys	B	BM[a]	B	B	B	B	B	B	B	B	B	B	B[c]	E	—
Nickel	C		C	—	C	BC	B	B	B	BC	BC	BC	B[c]C[c]	BE	—
Silver	B	BM[a]	B	B	B	—	B	—	—	—	—	BC	B[c]	BE	E
Glass sealing nickel-cobalt-iron alloys UNS No. K94610	M	CM[a]	M	C[b]M[a]	M	BM	BM	BM	BM	BM	BM	BCM	B[a]C[c]M	BM	—
Nonmetals	BCE[d]	BCM[a]	BC	BC[b]	BC	BC	B	B	B	BC	BC	BC	B[c]C[c]	—	—
Titanium	B	BM[a]	—	BE[a,b]	B	B	B	B	B	B	B	B	B[c]	BE	—

B = Beta backscatter; C = Coulometric; E = Eddy current; and M = Magnetic.

[a] Method is sensitive to permeability variations of the coating.

[b] Method is sensitive to variations in the phosphorus content of the coating.

[c] Method is sensitive to alloy composition.

[d] Method is sensitive to conductivity variations of the coating.

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Accurate placement of the part is essential for precise measurement. An aperture is provided to control the area exposed to the beta rays. The aperture is mounted in a probe together with the source to control the distance of the source to the sample.

The Geiger-Müller tube is part of a counting system that records the backscatter and then computes the thickness. A full line of accessories to store data and provide statistical information is available. Many systems provide computer prompting for both measuring and calibration procedures.

The beta backscatter method applies to coatings and substrates whose atomic numbers differ by at least 5. ASTM Standard Method B 567 details the consideration necessary for accurate measurement with this ethod.

COULOMETRIC METHOD

The coulometric method is based on Faraday's law. The law states that one gram-equivalent weight of metal will be stripped or deposited for every 96,500 coulombs (ampere-seconds) of electricity passed through the electrolyte. This law is so basic that it has been used to define the international ampere.

The international ampere is defined as the unvarying electric current that, when passed through a solution of silver nitrate, will remove 0.000118 gram of silver per second from the anode. This figure (0.000118 gram of silver per second) is called the electrochemical equivalent of silver.

The following equation defines the weight of metal deposited according to Faraday's law:

$$M = eit, \qquad (2)$$

where M = mass (g), e = electrochemical equivalent (g/ A-sec), i = current (A), and t = time (sec). To apply the coulometric method to thickness testing, four parameters must be controlled, namely, area, amperage, time, and anode efficiency. At 100% anode efficiency, by substituting the mass obtained from Faraday's law into the thickness formula, the thickness becomes

$$T = eit \times 10/A \times d. \qquad (3)$$

The area to be measured is determined by a flexible rubber gasket. This area can range from 0.13 to 0.32 cm in diameter. The gasket is an integral part of the deplating cell, that holds the solution during the test. The gasket must be flexible so that it will prevent leakage of the

Table II. Thickness Conversion Chart

Existing Unit of Measure	*Desired Unit of Measure* *Angstrom*	*Microinch*	*Micrometer*	*Mil*	*Millimeter*	*Inch*
Angstrom	1	0.004	0.0001	0.000004	0.0000001	0.000000004
Microinch	250	1	0.025	0.001	0.000025	0.000001
Micrometer	10,000	40	1	0.04	0.001	0.00004
Mil	250,000	1,000	25	1	0.025	0.001
Millimeter	10,000,000	40,000	1,000	40	1	0.04
Inch	250,000,000	1,000,000	25,000	1,000	25	1

How to use:
1. Locate existing unit in vertical column (left).
2. Find multiplier on the horizontal line that is under the new desired unit of measure.
3. Multiply existing quantity times multiplier.
Result is the approximate equivalent measurement in the desired unit.
Example: 100 microinches = ? micrometers 0.025 is the multiplier 100 × 0.025 = 2.5 (micrometers).

1 Thickness of single coatings of **Zn, Ni, Cr, Cu, Ag, Au, Sn** on

2 Thickness of binary alloy coatings such as **SnPb, ZnNi** and **NiP** (electroless nickel) on **Cu**

3 Thickness of ternary alloy coatings such as **AuCdCu** on **Ni**

4 [illegible]

5 [illegible]

6 Thickness of triple coatings such as **Cr/Ni/Cu** on **plastic** or **Iron**

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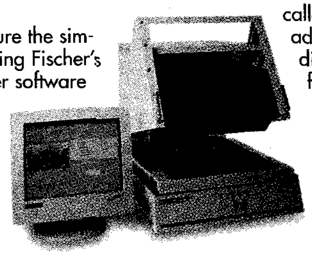

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solution, yet sufficiently rigid for precise maintenance of the area.A constant pressure device is included to aid in controlling the gasket pressure. Since this measurement yields weight per area, accurate control of this diameter is essential.

On most instruments, the current source and timer are included in a current supply package. This package provides a means for producing a specific constant amperage for each coating to be tested.

When the coating is penetrated, there is a voltage change. The rate of change of this voltage is monitored and used to terminate the test. An electronic timer is used to record the time elapsed. A computer processes the time and amperage, then displays the thickness. Also included in the package are electronic controls to modify the current and termination sensitivity. These controls are provided to compensate for minute changes in anode efficiency and area.

It is necessary to use a specific electrolyte for each combination of coating and substrate. The electrolyte must satisfy three conditions:

1. The solution must not chemically attack the coating.
2. Anodic dissolution of the coating should be at constant efficiency, ideally 100%.
3. The voltage change on penetration of the coating should be significant.

This method is capable of consistently measuring the thickness of a variety of metallic coatings to ±10% of their true value. For certain coating and substrate combinations, the accuracy can be higher. The most accurate measurements are in the range of 40 to 2,000 microinches; however, chromium can be measured in thicknesses as low as 3 microinches. The accuracy of measurement in a specific thickness range may be increased by calibrating the instrument with standards in that range.

Coatings on wire are measured by means of an auxiliary cell. Tests are performed on sample lengths from 0.5 to 4.0 in. in length.

One advantage of this method is the ability to measure combination coatings such as copper/nickel/chromium and copper/tin. The instrument manufacturer's instructions should be followed precisely for accurate results. Additional guidelines for achieving accurate measurements are contained in the following ASTM methods:

1. ASTM B 504, standard method for coulometric thickness.
2. ASTM B 298, for silver coatings on copper wire.
3. ASTM B 355, for nickel coatings on copper wire.

The coulometric instrument has found application in measuring other qualities of metallic coatings. ASTM B 764 describes a procedure for simultaneous thickness and electrochemical potential (STEP) determination for the layers of multilayer nickel deposit.

DROP TESTS

The drop test for measuring plating thickness is based on the rate of attack of specially prepared corrosive solutions on a metal coating. For consistent results, the drop size, drop rate, temperature, time, and solution composition must be controlled.

The test is performed by allowing the solution to drop on a particular spot at a rate of 100 drops per minute. The operator then observes the time at which the coating is penetrated. For the most common thicknesses, the elapsed time is less than one minute.

Reproducibility of the test is dependent on the skill of the operator. The operator must detect the point at which the base metal is exposed and record the time. An experienced operator can reproduce his readings within ±5%. For best accuracy, the operator should standardize his technique with a standard of known thickness.

The accuracy of the system is generally considered to be ±15%, because the operator cannot control some of the factors that affect the test. These factors include drainage of the solution, alloying at the coating/substrate interface, and composition of the coating.

Low cost and the ability to measure thickness quickly on irregular shapes are the chief advantages of the drop test. The greatest disadvantages are destruction of the coating and objections to the use of corrosive solutions in some areas. The largest application is in the fastener industry.

Standard guidelines for the use of this test are contained in ASTM B 555. Some typical procedures are provided below.

Reagents

1. Cadmium deposits:
    Ammonium nitrate, 110 g/L
    Hydrochloric acid, 10 ml/L
2. Zinc deposits:
    Ammonium nitrate, 100 g/L
    Nitric acid, 55 ml/L
3. Zinc and cadmium deposits:
    Chromic acid, 200 g/L
    Sulfuric acid, 50 g/L
4. Tin deposits:
    Trichloroacetic acid, 100 g/L
5. Copper deposits:
    Ferric chloride ($FeCl_3 \cdot 6H_2O$), 450 g/L
    Antimony trioxide, 20 g/L
    Hydrochloric acid, 200 ml/L
    Acetic acid (CP, glacial), 250 ml/L

Operating Conditions

Drop rate: 90 to 110 drops per minute (100 preferred).

Temperature: 20 to 30°C (70 to 90°F).

Penetration rate: For zinc and cadmium (using separate reagents listed above), each second = 0.00001 in. For copper deposits, two seconds = 0.00001 in. Figure 1 shows the penetration factor as a function of temperature for testing zinc and cadmium deposits with the chromic acid/sulfuric acid reagent.

Lacquer or other films are removed from the area to be tested, which is then cleaned with a suspension of magnesium oxide in water. The specimen is held at an angle of 45° below the dropping tip. To ensure that the reagent impinges on the same spot throughout the test, it is preferable to clamp the specimen in place rather than to hold it by hand.

The apparatus may consist of a separatory or dropping funnel, which is fitted with a short length of tubing terminating in a drawn-out tip. Special funnels are available with two stopcocks. One of these is fully opened and the other used to set the desired drop rate. An automatic drop-test apparatus is available in which the drop rate is automatically maintained at 100 drops per minute by means of a synchronous motor-driven mechanism.

EDDY CURRENT

Eddy current thickness gauges are electromagnetic instruments designed to measure the apparent change in impedance of the coil that induces the eddy current into the base metal. They are calibrated by comparing the apparent change in impedance to known thickness of coatings on selected base materials.

It is the difference between the conductivity of the base material and the coating that influences the change in impedance; therefore, the instrument has its greatest accuracy when

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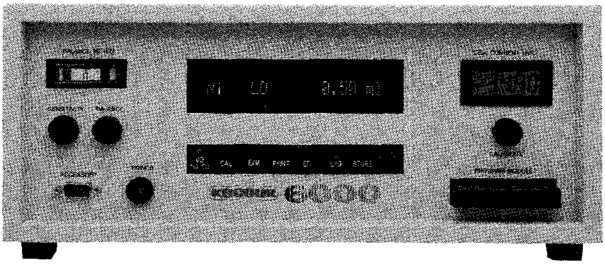

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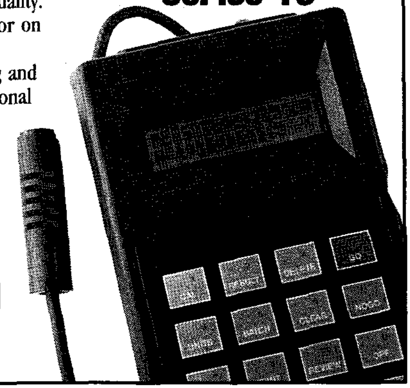

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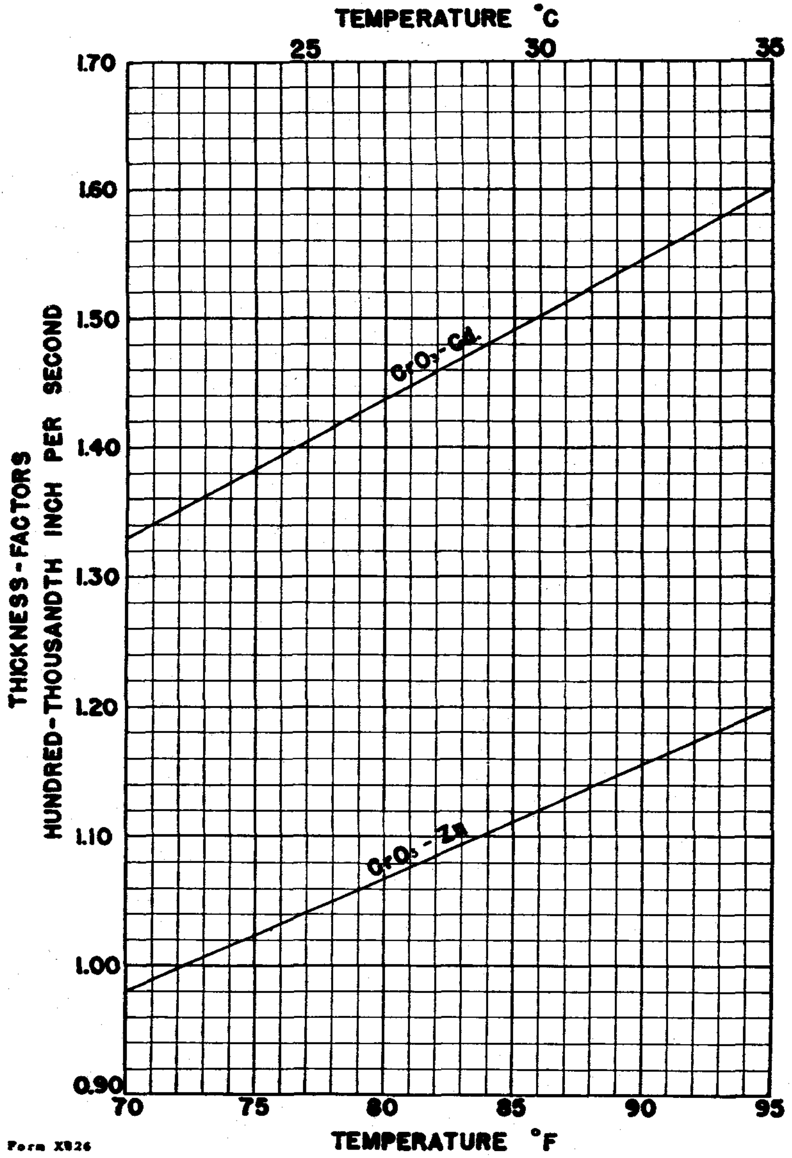
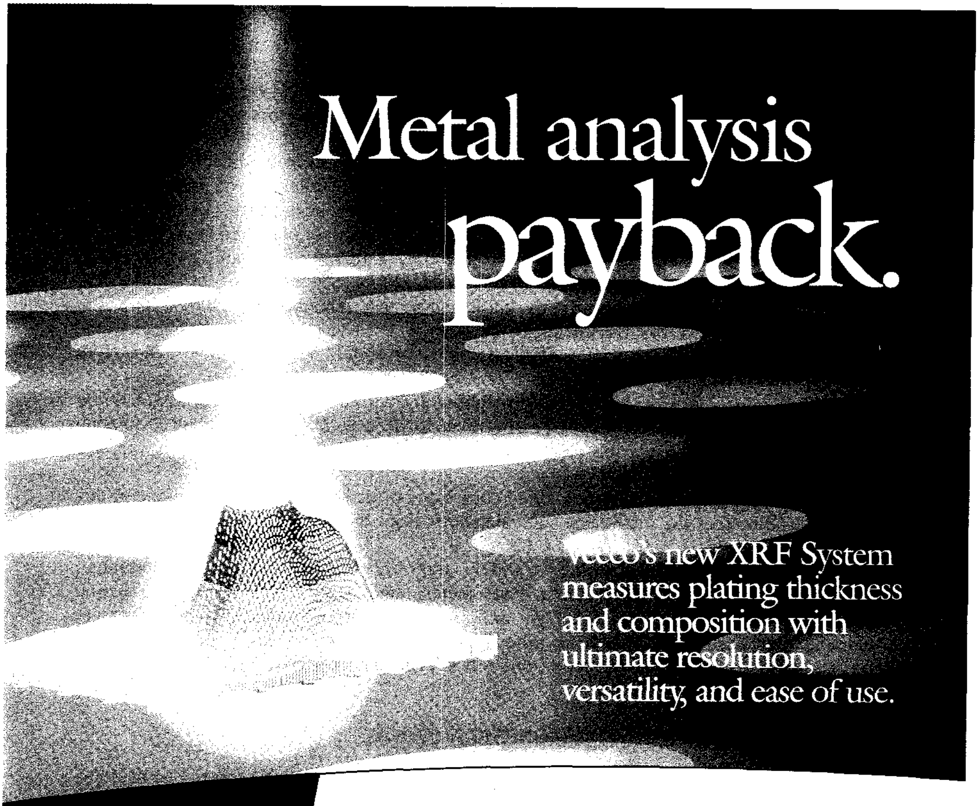


Fig. 1. Time, temperature, and thickness relation for chromic acid drop test on zinc and cadmium.



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testing nonconductive coatings on conductive base materials and vice versa. The test can be applied to poor electrical conductors over good electrical conductors with some loss in accuracy.

The thickness test is performed with the aid of a specially designed probe. Measurements are made by holding the probe perpendicular to the surface and with the probe point in contact with the area to be measured. The measurements are rapid and nondestructive; therefore, some problems with accuracy may be resolved by statistical evaluation of many readings. Thickness gauges are available with digital display, memory, hard-copy printout, and computer prompting of the calibration procedure.

In the range of 5 to 50 μm, the thickness can be determined to within 10% or 1 μm, whichever is greater, of the true thickness. This test is sensitive to marked differences in the surface contour of the test specimen. Particular attention should be paid to the distance from an edge, surface roughness, and curvature at a test point.

Erroneous results may be avoided by calibrating with standards that approximate the surface condition and curvature of the specimen to be tested. The type of electroplating solution used can influence the electrical conductivity of the deposit and, therefore, the thickness measured.

Zinc plated in cyanide, chloride, or alkaline baths is the most prominent example of this problem. Calibrating the instrument with standards from the same or similar solutions can greatly reduce error.

Eddy current thickness testing is widely applied to anodic coatings on aluminum, nonmetallic coatings on nonmagnetic base metals, and to a lesser extent, to metallic coating/substrate combinations that have different electrical conductivities. The instrument manufacturers' instructions should be followed precisely for best results. A standard method for the application and performance of this test is available in ASTM B 244.

MAGNETIC METHOD

The magnetic method uses the magnetic influence of the coating and substrate on a probe as the basis of a measuring system. Two types of probe systems are in common use. The first to be developed makes use of a mechanical system to measure the influence of the coating thickness on the attractive force between a magnet and the base material.

An electromagnetic probe was later developed that measures the influence of the coating thickness on the reluctance of a magnetic flux path through the coating and base material.

Three types of coatings can be measured with this system:

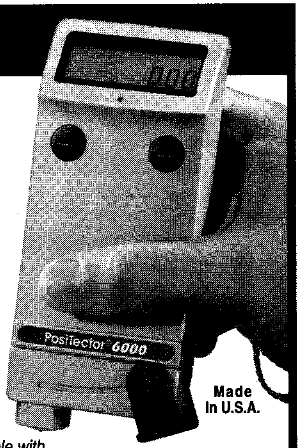
1. Nonmagnetic coatings on ferromagnetic base metals.
2. Nickel coatings on ferromagnetic base metals.
3. Nickel coatings on nonmagnetic base materials.

The test is performed with the aid of specially designed probes. With the permanent magnet type, measurements are made by placing the probe perpendicular to the surface to be measured and observing the force necessary to remove the probe.

The electromagnetic-type probe requires placing the probe perpendicular to the surface to be measured and observing the reluctance measurement. The measurements are rapid and nondestructive; therefore, some problems with accuracy may be resolved by the statistical evaluation of many readings. Commercial instruments are available with analog and/or digital thickness display, memory, hard copy printout, and computer prompting of calibration procedures.

The effective thickness range is dependent on the choice of probe system (magnet or reluctance) and the coating/substrate combination. The ranges for the magnet type are:

1. Nonmagnetic coating on magnetic base, 5 to 25 μm.
2. Nickel coating on magnetic base, 5 to 50 μm.
3. Nickel coating on nonmagnetic base, 5 to 25 μm.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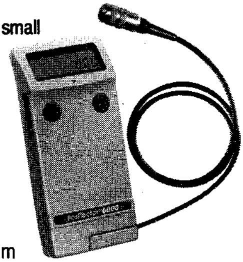
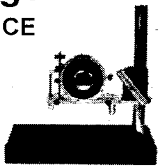




The ranges for the reluctance type are from 5 μm to 1 μm for all three coating/substrate combinations. Both types of instruments are sensitive to marked differences in the surface contour of the test specimen.

Particular attention should be given to the distance from an edge, surface roughness, and curvature at the testing point. Erroneous results may be avoided by calibrating with standards that approximate the surface condition and geometry of the specimen to be tested. When properly calibrated, the magnetic system can determine the actual thickness within 10%. The instrument manufacturer's instructions should be carefully followed for the most accurate results. Two standard methods have been developed for additional guidance to more reliable readings. They are ASTM B 499 and ASTM B 530.

GRAVIMETRIC

This method requires the measurement of the area to be tested and the determination of the mass of the coating in that area. The area may be determined by standard measuring techniques. The coating mass may be determined by one of the following procedures:

1. Weigh coating directly after dissolving the base material without attacking the coating.
2. Determine coating mass by analyzing the solution used to dissolve the coating and all or a portion of the base material.
3. Determine coating mass as the difference between the weight before and after dissolving the coating without attacking the base material.
4. Determine coating mass as the difference between the weight before and after coating.

Usually this method is assigned to a laboratory equipped to handle the corrosive solutions and to measure the mass and area with sufficient accuracy. After the area and mass have been determined, the thickness may by determined by using Equation (1).

Procedures 1, 2, and 3 are destructive; procedure 4 is nondestructive. This method has the capacity to yield extremely accurate results and is frequently used to determine the exact mass of metal used for cost purposes, particularly with the more precious metals. This method (procedure 4) is used as a technique for making thickness standards.

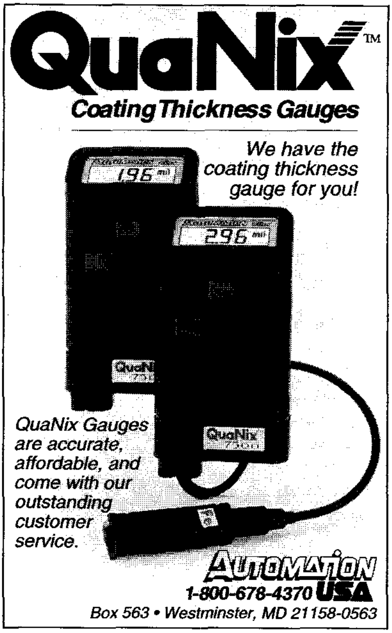
ASTM has developed procedures for several specific coatings. They are Method A 90 for zinc, Method A 309 for terneplate, Method A 630 for tin plate, and Method B 137 for anodized aluminum. ASTM B 767 serves as a guide for use of this procedure for a variety of plating and substrate combinations.

MICROMETRIC

A micrometer may be used to check the thickness of coatings over 0.001 in. If the micrometer is equipped with a dial indicator, thicknesses of 0.0005 in. may be measured on uniformly coated cylindrical parts. It is necessary to measure the same spot before and after plating. Measurements may be obtained by masking the deposit and dissolving the unmasked coating, then measuring the step produced by this procedure.

MICROSCOPIC

The microscope can be used as a length measuring instrument when it is equipped with a filar eyepiece. The specimen must be carefully polished to prepare a smooth reflective surface and then etched to reveal the various metals exposed. This generally requires the services of an experienced metallographer.



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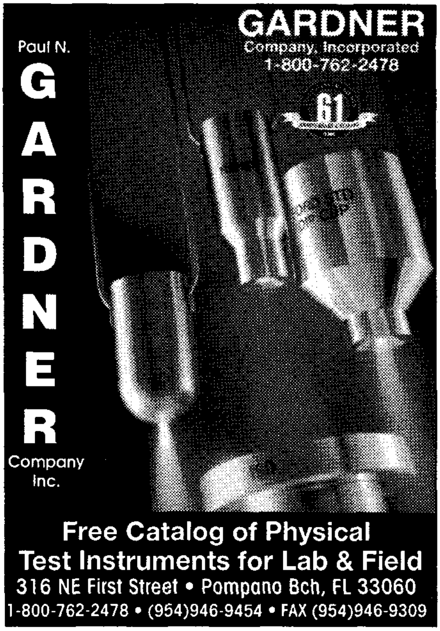

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The measurements are generally made on a transverse section of the deposit so that the various layers of plating are exposed for viewing. Measurements are also made on tapered sections to increase the length to be measured. The thickness is then calculated by correcting the observed length for the taper angle.

This method is destructive and time consuming. The thickness results have a precision of ±2%; however, the accuracy has a constant uncertainty of about 0.8 μm (30 microinches). Therefore, despite the precision of the method, it should not be considered as a reference to resolve questions about thicknesses less than 8 μm (300 microinches).

The filar eyepiece is calibrated by comparing the divisions on the filar micrometer to the known distance between divisions on a stage micrometer. This method is a true measure of length and does not require a plated standard for calibration.

Due to the high cost of this technique, its use has been reserved for those occasions that require more information than may be obtained from other thickness-gauging methods. Information concerning porosity, surface roughness, grain structure, and adhesion may be gathered from the specimen prepared for a thickness test.

ASTM B 487 is a standard method outlining the conditions for accurate results.

The wavelength of light limits the resolution of the light microscope to about 10 microinches. The scanning electron microscope utilizes the shorter wavelength of electron waves to measure metallurgical specimens with a 4 microinch resolution. ASTM B 748 is the standard test method for this procedure.

Attachments are available for the metallurgical microscope that allow it to be used as an interferometer. The method is mentioned, because its accuracy with thin coatings can be within ±5% of the true thickness. Conditions necessary for this procedure are contained in ASTM Standard Method B 588.

THE SPOT TEST

This test was developed as a rapid and inexpensive thickness test for chromium coatings on nickel and stainless steel. The test has an accuracy of ±20% for coatings up to 1.2 μm thick. A wax ring is outlined on the part to be tested. A drop of hydrochloric acid is placed in the ring, and the time between the onset and cessation of gassing is recorded. ASTM B 556 provides a standard guide for the performance of this test.

X-RAY FLUORESCENCE

This method is similar to beta backscatter in that the area to be tested is the target of radiation, and the energy emitted from that surface is measured. In this method, the radiation used is X-rays produced by an X-ray tube. The radiation measured is secondary emissions from the interaction of the X-rays with the coating and substrate. Unlike beta backscatter, the emissions measured are specific for each metal.

Among the unique characteristics of this method are the following:

1. No physical contact with the measured surface is required, thereby protecting that surface.
2. Extremely small areas may be measured.
3. Since the emissions are specific for each metal, alloy compositions may be determined.
4. With proper calibration, intermediate coatings may be measured in a multilayer system.

Thickness may be measured in the range 0.25 to 10 μm, depending on the metal being measured. With proper calibration, the thickness may be determined to within 10% of its true value. ASTM B 568 outlines a standard method for this measurement system. Due to the noncontacting characteristic and the rapid test time, this procedure is used to continuously monitor thickness on continuous-coil plating machines and automated plating machines.

STANDARDS

Thickness standards are required for calibrating thickness gauges. In most cases, the standards should be plated from a similar plating solution and on the same base metal as the product to be tested.

After receipt, it is important to have a system to ensure the standard's reliability after use. One system makes use of primary, secondary, and working standards. The working standards are used for calibrating the thickness gauge daily.

Once a week, the working standards are calibrated against the secondary standards. The secondary standards are then calibrated against the primary standard once a month. The time between calibrations can be varied based on experience with the expected life of the standard. When a new standard is purchased, it becomes the primary standard, and the remaining standards are lowered in rank.

SUMMARY

To measure the thickness of a coating, many properties have been utilized. Measurements have been described that use the atomic configuration, electrochemical equivalent, corrosion rate, electrical conductivity, magnetic properties, density, and actual linear measure of the coating.

In addition to these methods, tests have been successfully performed by using the electrical resistance and transparency of the coating. Each of these methods has its proper application.

It is obvious that one system is not capable of satisfying the needs of every plater. Certainly, a plater coating 10,000 fasteners per barrel load at a rate of 50 barrel loads per shift has a problem that is substantially different from a plater that hard chromium plates printing rolls. Experience and judgment are required, and the responsibility for choosing the most economical thickness-measuring system adequate for a particular problem is not a simple task.

PLATING BATH CONTROL USING AMPERE-TIME INSTRUMENTS

David A. Stewart
Systematics Inc., Bristol, R.I.

Joseph J. Werbicki
Copperweld Metallon Div., Pawtucket, R.I.

Plating takes place when an electrical force (voltage) causes the positive-charged metal ions in a plating bath to move towards the negative-charged cathode part of the plating circuit and combine with available electrons. At the cathode they are deposited as metal atoms. The movement of ions from one place to another (and electrons in the opposite direction) constitutes electrical current. The standard unit of measure for current is the Ampere.

When we plate, we plate by amperage.

An analogy can be drawn between amperage and voltage in a plating circuit. Voltage is like the force a bicycle rider exerts on the pedals. Amperage is like the speedometer reading. On a consistent road surface, the more force the rider exerts, the faster he goes; however, if he encounters a hill or a valley, he will have to adjust the force on the pedals to keep the same speed. Voltage is force. A change in voltage will change amperage. A change in the bath's resistance will also change the amperage. In this case the voltage will need to be adjusted to maintain the same amperage. Measuring ampere-hours is like measuring miles with an odometer. An ampere-time counter tells us the amount of current that has passed through a plating bath.

The amount of metal deposited depends on three factors: amperage, plating time, and current efficiency of the bath.

Amperage and plating time are integrated and tracked with an ampere-time counter.

Current efficiency of a bath is determined by a simple laboratory-plating test. It is a fairly reproducible measure of the rate at which metal is deposited under a given set of operating conditions.

These conditions include metal content, pH, temperature, agitation, and current density.

Current density is the total number of amps passing through a plating bath, divided by the total area of plateable metal surface in the bath. Typically, current density is stated in amps per square foot or A/ft^2, though other units, such as amps per square foot or amps per square decimeter, are often used.

For a given set of operating conditions, a bath will have an optimum current density range within which acceptable deposits can be produced. This range is spelled out on technical data sheets for most proprietary plating systems.

Current efficiency may be stated on a technical data sheet in a number of ways. For precious metals you will often see it stated in milligrams per ampere-minute, or you may see it stated in terms of deposit thickness per unit of time. For example, at 40 A/ft^2, a Watts nickel bath will deposit 0.0001 in. in 3 minutes.

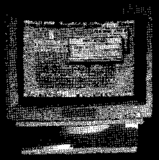
These seemingly different ways of stating current efficiency are completely interchangeable, using but two basic formulas, either singly or in combination:

$$(1)\quad \textit{Ampere-time} \times \textit{Current Efficiency} = \textit{Milligrams of metal deposited}$$

$$(2)\quad \textit{Thickness (micro inches)} = \textit{Milligrams of metal deposited} \times \textit{FactorPlated area } (in^2)$$

The factor to commit to memory is 3.162 for gold. For any other metal the gold factor is multiplied by 19.3 and divided by the specific gravity of the new metal.

As an example, the factor for nickel is 3.162 × 19.3 divided by 8.9 or 6.86.



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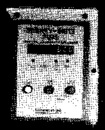

Automatic
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Ampere
Time
Calculator

The two formulas above can always be combined in order to calculate one of the variables that may not be known. For example:

$$(3) \quad \textit{Ampere-time} \times \textit{Current Efficiency} = \textit{Thickness AreaFactor}$$

Using the combined formula, you can determine ampere-time to plate a required thickness or thickness that will be deposited in a given amount of ampere-time. Area, current efficiency, and factor are constants. The area of work being plated and the plating range of the baths fix total amperage. To determine the required amperage multiply the recommended current density by the area to be plated.

The ampere-time counter always shows the total accumulated ampere-time regardless of any changes in amperage that may have occurred during the time of accumulation. This is because the counter takes a signal from an electrical component called a shunt. The signal from the shunt is in millivolts and varies from zero when there is no current flow, to a maximum signal (usually 50 millivolts) when the amperage is at maximum. This signal causes the counter to increment at a rate that is always equal to the amperage multiplied by the elapsed time.

An added feature on some ampere-time counters is an interval preset. With this feature the operator can set the ampere-time that he wants to plate. When the instrument reaches the interval preset count, an alarm may sound, or the rectifier may be shut down.

Equally as important as metal deposited is the amount of other constituents that is removed from a bath during plating. Chemical composition is one of the most difficult bath parameters to control. Analysis and replenishment is the only sure way; however, on-line chemical analysis is expensive, and periodic analysis may not be enough. The ampere-time instrument is the answer.

If the current efficiency of a bath is known metal deposited (or removed) from the bath is directly related to ampere-time by formula (1).

For additives, such as brighteners, manufacturers' literature will give the consumption rate in terms of brightener volume per a certain number of ampere-hours. The consumption rate should be compensated for losses due to dragout.

An improvement to the ampere-time counter is the automatic feeder. This instrument combines an ampere-time counter with an interval preset and a pump. The operator can set the device for an interval ampere-time count that will activate the feed pump for a preset time to feed the right amount of replenishment chemicals into the bath. Adding replenishments in smaller amounts and frequent intervals helps keep the bath composition consistent.

Modern electronics has helped to make these instruments very reliable and easy to set up. Some are equipped with multiple pumps for chemicals that can't be premixed. Others are configured to accommodate multiple rectifiers that operate in the same bath.

In summary we have seen that an ampere-time counter and a few simple formulas can give even the smallest plating shops most of the information that is required to maintain their plating chemistry. A few added features can automate processes that are time consuming and prone to human error.

CHOOSING AN ACCELERATED CORROSION TEST

by Frank Altmayer

Scientific Control Laboratories Inc., Chicago

Accelerated corrosion tests are typically used to determine if a coating/substrate combination has been produced to yield a satisfactory service based on historical data from previous testing and field exposures of similar coating/substrate combinations. The intent is to find out, in a relatively short amount of time, what the appearance or performance of the product will be after several years of service.

Real-life exposures are complicated events that may involve several factors including geometric configuration, porosity/adherence of corrosion product, soiling, abrasion, frequency of cleaning, cleaning procedures, cleaning chemicals, sun exposure, and temperature variations. Because of this, it is critical that the accelerated test chosen simulates "real-life" corrosion mechanisms as much as possible. The following guidelines were prepared to assist in choosing the best accelerated corrosion test for a given application.

CORROSION MECHANISMS

Coated metallic products are subjected to two basic corrosion mechanisms during their service life: (1) electrochemical (galvanic) and (2) chemical attack.

Electrochemical (Galvanic)

Electrochemical corrosion can be caused by dissimilar metals contacting an electrolyte. This is the common "battery" effect. Detrimental galvanic corrosion effects occur when the substrate is electrochemically more active than the protective coating, or when the corrosive environment contains a metal that is less active than the coating and substrate. The electrolyte (water, salt solution, acid, etc.) must be in contact with both metals for this mechanism to occur.

Examples of the beneficial use of this corrosion mechanism include galvanized or electroplated zinc over steel, where the zinc, being electrochemically more active than steel, will corrode in preference to the steel when exposed to a corrosive environment (electrolyte). This protection is extended even if large scratches are present through the zinc and into the steel. Another example is duplex nickel. Nickel containing sulfur ($\sim$0.02%) from the addition of brightening agents is electrochemically more active than nickel without sulfur. A two-layer system, consisting of semibright nickel (no sulfur) followed by bright nickel, yields a galvanic couple wherein the bright nickel corrodes in preference to the semibright, providing galvanic protection to the second nickel layer, thereby delaying corrosion of the basis metal (and failure).

The electrochemical mechanism can also involve a difference in the quantity of oxygen contacting the surface of the exposed specimen in the presence of an electrolyte. Two dissimilar metals are not required. The area of the specimen that is oxygen deficient becomes anodic to the area that contacts the larger quantity of oxygen. The anodic area dissolves into the electrolyte, leaving a corrosion pit. Hydroxides (alkali) are deposited at the cathodic (oxygen-rich) area.

The physical variations of the oxygen concentration cell mechanism are given various names.

Crevice corrosion: When specimens with complicated geometric shapes are allowed to contact corrosive liquids (water, salt solution), the sharply recessed areas (pores) in the surface of the specimen contact less oxygen than the remaining surface due to differences in oxygen diffusion. The metal inside the pores becomes anodic to the bulk. An example would be the crevice underneath the head of a bolt or screw when these are tightened to a nut or other surface.

Sandwich corrosion: The gap between joining flat surfaces becomes anodic to the exterior surface. The corrosion products tend to push the joined surfaces apart. An example is the gap between riveted aluminum sheets comprising an aircraft wing or body panel.

Poultice corrosion: Accumulated soil on a corrodible surface acts as a "poultice," holding thousands of pockets of electrolyte (water, salt, etc.) onto the surface. Differences in oxygen concentration then act to corrode the surface. An example is the dirt that accumulates on the underside and wheel wells of an automobile.

Filiform corrosion: This type of oxygen cell corrosion is peculiar to organic coatings (paints, lacquers, etc.) that are subjected to chipping. The chipped area contacts more oxygen than the metal covered by coating. As the covered metal that is some distance from the chip corrodes and precipitates hydroxides under the paint, a wormlike appearance in the coating develops as the coating is lifted off the base metal. The "worm" traces take straight lines under constant temperature and twist under variant temperature.

Chemical Attack

The chemical nature of acids and certain chemicals is that they attack (dissolve) metals. The performance of a coating in resisting attack is determined by subjecting the test specimen to varying concentrations of acids, acid-forming gases, or chemical solutions.

Acid attack, chemical attack, and electrochemical techniques can also be used to determine the porosity of a coating, which can sometimes be related to service life. Examples of such techniques are the ferroxyl test, electrographic printing, and the copper sulfate test (on hard chrome over steel).

TEST METHODS

The following are commonly performed accelerated corrosion and porosity tests. Table I summarizes applicability and denotes the most common test used on a given coating/substrate combination.

Salt Spray (ASTM B 117)

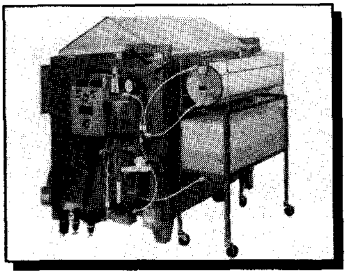
This is the most widely specified corrosion test. It has broad applicability. The salt solution that is utilized closely simulates the corrosive effects of outdoor exposure on automotive hardware (except some decorative nickel-chromium applications; see CASS and Corrodkote in Table I).

Test results normally are obtained in a few hours for lesser protective systems (phosphate, oil, hard chromium plating) and it may take many days (40–80) for superior systems such as tin-nickel plating, heavy galvanize, and galvanize/paint combinations.

The corrosion mechanisms employed are oxygen concentration cell and galvanic effects, accelerated by use of an electrolyte with a chloride content of 5% weight (more has been shown to be unnecessary); elevated temperature; inclination of test specimen; and utilization of a fine-fog mist.

100% Relative Humidity (ASTM D 2247)

This test has wide applicability for protective coatings that are exposed indoors, in sheltered areas, or in areas where water (condensation) can accumulate on the surface of the specimen.



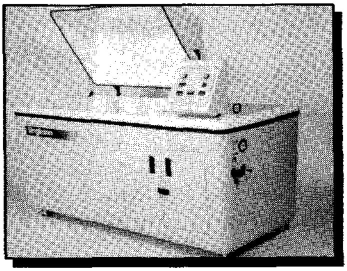


Table I. Applicable Corrosion Test for Various Coatings/Substrates

		Applicable Test(s), Most Commonly Performed Test in Parentheses (X)												
Coating	*Substrate*	*AA*	*CASS*	*CDK*	*EG*	*F*	*FACT*	*HUM*	*K*	*LA*	*SS*	*SO_2*	*TS*	*W*
Anodize (chromic)	Aluminum	X	—	—	—	—	X	—	—	—	(X)	—	—	—
Anodize (hardcoat)	Aluminum	(X)	—	—	—	—	X	—	—	—	X	—	—	—
Anodize (sulfuric)	Aluminum	—	—	—	—	—	X	—	—	—	(X)	—	—	—
Black chrome	Steel	—	—	—	—	—	—	(X)	—	—	X	—	—	—
Black oxide	Steel	—	—	—	—	—	—	(X)	—	—	X	—	—	—
Bronze plate	Ferrous	(X)	—	—	—	—	—	—	—	—	(X)	—	—	—
Cadmium plate	Ferrous	X	—	—	—	—	—	—	—	—	(X)	—	—	—
Chromated cadmium	Ferrous	X	—	—	—	—	—	—	—	—	(X)	—	—	—
Chromated zinc	Ferrous	X	—	—	—	—	—	—	—	—	(X)	—	—	—
Copper plate	Nonconductor[a]	—	—	—	—	—	—	X	—	—	—	—	—	—
Copper/nickel/chromium	Ferrous	X	X	(X)	X	X	—	—	—	—	X	—	—	—
Copper/nickel/chromium	Nonferrous	X	X	(X)	X	—	—	—	—	—	X	—	—	—
Copper/nickel/chromium	Plastic	(X)	—	—	—	—	—	—	—	—	X	—	—	—
Electroless nickel	Ferrous	X	—	—	—	—	—	—	—	—	(X)	—	—	—
Electroless nickel	Nonferrous	X	—	—	—	—	—	—	—	—	(X)	—	—	—
Galvanize	Ferrous	X	—	—	—	—	—	—	—	—	(X)	—	X	—
Hard chrome plate	Ferrous	—	—	—	X	—	—	—	—	—	(X)	—	—	—
Hard chrome plate	Nonferrous	—	—	—	—	—	—	—	—	—	X	—	—	—
Iron phosphate	Ferrous	—	—	—	—	—	—	(X)	—	—	X	—	—	—
Lacquered brass/nickel	Ferrous	—	—	—	—	—	—	X	—	(X)	X	—	—	—
Manganese phosphate	Ferrous	—	—	—	—	—	—	(X)	—	—	X	—	—	—
Nickel plate	Ferrous	—	—	—	—	—	—	X	—	—	(X)	—	—	—
Oils/greases	Ferrous	—	—	—	—	—	—	X	—	—	—	—	—	—
Paint	Ferrous	X	—	—	—	—	—	X	—	—	(X)	—	—	X
Paint	Nonferrous	X	—	—	—	—	—	X	—	—	(X)	—	—	X
Passivate	Stainless steel	—	—	—	—	—	—	—	—	—	(X)	—	—	—
Tin plate	Ferrous	(X)	—	—	—	—	—	—	—	—	X	—	—	—
Tin-nickel plate	Ferrous/nonferrous	—	—	—	—	—	—	—	(X)	—	—	X	—	—
Zinc phosphate	Ferrous	—	—	—	—	—	—	(X)	—	—	X	—	—	—
Zinc plate	Ferrous	X	—	—	—	—	—	—	—	—	(S)	—	—	—

AA, acetic acid-salt spray; CASS, copper accelerated salt spray; CDK, Corrodkote; EG; electrographic; F, ferroxyl; FACT; Ford accelerated corrosion test; HUM, humidity; K, Kesternich; LA, lactic acid; SS, salt spray; SO_2, Sulfur dioxide; TS, triple spot; W, weatherometer.

[a] Printed circuit boards.

Many variations of this test are employed to more accurately reflect service conditions. These include varying humidity levels from 60 to 95% relative humidity; cycling humidity with periodic dips into corrosive liquids (ASTM G 60); cycling humidity with drying cycles for coatings on wood (ASTM D 3459); and combining humidity with severe temperature fluctuation (ASTM D 2246).

The corrosion mechanism employed is oxygen concentration cell, accelerated by high humidity level, elevated temperature, and inclination of test specimen.

ASTM B 287 (Acetic Acid-Salt Spray)

This test is intended for coating systems that provide excellent corrosion-protection results in long-term salt spray (B 117) exposure. This test is approximately twice as severe as the salt fog (B 117) test, although this may vary significantly with each application.

The corrosion mechanism employed is oxygen concentration cell accelerated by operation at lowered pH (3.1–3.3 vs. 6.5–7.2 for the salt fog test); use of an electrolyte with a chloride content of 5% weight (more has been shown to be unnecessary); elevated temperature; inclination of test specimen; and utilization of a fine-fog mist.

Copper Accelerated Salt Spray (CASS) (ASTM B 368)

This test was developed for use on copper-nickel-chromium coatings over ferrous and nonferrous substrates.

The oxygen concentration cell corrosion mechanism is accelerated by operation at lowered pH (3.1–3.3 vs. 6.5–7.2 for the salt fog test); use of an electrolyte with a chloride content of 5% weight (more has been shown to be unnecessary); elevated temperature; inclination of test specimen; utilization of a fine-fog mist; and the addition of cupric chloride to provide galvanic effects.

Corrodkote (ASTM B 380)

This test was also developed for specific use on copper-nickel-chromium coatings on ferrous and nonferrous substrates.

The corrosion mechanisms employed are oxygen concentration cell and galvanic effects produced by cupric and ferric ions, plus complicated chemical effects produced by the nitrate, chloride, and ammonium ions.

The test utilizes a kaolin paste that holds the corrosive ions to the surface of the test in a "poultice" fashion, similar to accumulated dirt and scale on exterior automotive parts.

FACT (ASTM B 538)

This test is limited to anodized aluminum coatings and is basically a porosity test used to obtain rapid corrosion protection results based on the porosity level found. Substantial service background is needed to correlate test data with service life for any specific application.

The test consists of an electrolytic cell with salt spray (ASTM B 117) or CASS (ASTM B 368) solution as an electrolyte.

The cell is placed onto the test specimen with a gasket to prevent leakage. A potential is applied between a platinum anode and the test specimen (cathode). As hydrogen is discharged from the cathodic sites (pores), alkalinity is developed, attacking the coating and decreasing the cell voltage. The decreasing cell voltage is integrated over time, yielding a comparative result.

Weatherometer (ASTM G 23)

This test is utilized to evaluate the performance of paint and lacquer systems under simulated outdoor exposure. The test yields data on the resistance of the coating system to condensation effects (rain) and the stability of the pigment in the paint (colorfastness) when exposed to sunlight. Intense ultraviolet radiation from twin carbon arc lamps and variant humidity levels (cycling from approximately 70 to 100% relative humidity) provide long-range test results in a short time frame (100–2,000 hr).

Lactic Acid

Lacquered brass- and copper-based alloys are tested for porosity and resistance to tarnishing by everyday handling (perspiration), using this test. Although not ASTM standardized, the procedure is gaining industrial acceptance. The principal mechanism is chemical attack.

The procedure is as follows:

1. The item is dipped in a room-temperature solution of lactic acid (85%) saturated with sodium chloride.
2. The item is air dried for 2 hr in a convection oven at 120°F.
3. The item is suspended in the air above 100 ml of 30% acetic acid in an airtight chamber (desiccator). An acceptable substitute is the vapor produced by 100 ml of a 50% solution of acetic acid in water over a small, open dish.

A typical successful exposure is 20 hr above the acetic acid without the appearance of green (nickel) corrosion, loss of adherence of the organic coating, or tarnishing of the brass or copper plate.

Sulfur Dioxide/Kesternich (ASTM B 605)

A few coatings are so stable that normal corrosion-resistance testing results in unwieldy exposure hours. To yield results in a realistic amount of time, an acidic attack mechanism is used. Two of these tests are the sulfur dioxide (ASTM B 605) and the Kesternich (Volkswagen) test, Volkswagen specification DIN 50018. These procedures normally are limited to tin-nickel and similar inert coatings, or to coatings where a quick detection of a fault or surface imperfection is required.

Both procedures use sulfur dioxide gas at elevated temperatures and humidity levels, forming sulfurous acid on the surface of the test specimen.

Triple Spot (ASTM A 309)

Galvanized steel is protected from corrosion by the sheer thickness of the zinc coating. An estimate of the corrosion resistance can, therefore, be obtained by measuring the average thickness of the zinc coating on the steel. The thickness is measured using the "weight-area method" and an inhibited acid for stripping.

This indirect method for measuring corrosion resistance of galvanically protected steel is limited to thick coatings (galvanize). Relatively thin coatings, such as electroplate, are not as easily correlated to corrosion performance, because local variation in thickness will yield service failures that are not "predicted" by this method.

Electrographic and Chemical Tests for Porosity

Pores and cracks in chromium over nickel or nickel over steel can be detected using absorbent paper soaked in chemicals that react with the substrate, such as dimethylglyoxime for nickel substrates and potassium ferricyanide for steel substrates (commonly called the ferroxyl test).

The test specimen is covered by the soaked paper and, with pressure from a stainless steel cathode, a small current is passed (the test specimen is anodic). The chemicals react with the substrate at cracks and pores, thereby forming colored traces in the paper. Correction to actual service life is difficult.

Pores in hard chromium deposits over steel can be detected by applying an acidified copper sulfate solution (50 g/L with a pH ≤ 2) for approximately 30 seconds. Galvanically deposited copper will appear at areas with pores present.

TEST CELLS FOR PLATING

by David R. Gabe

Institute of Polymer Technology and Materials Engineering, Loughborough University of Technology, Loughborough, Leicestershire, U.K.

Plating cells are employed to define the link between processing conditions and deposit properties and characteristics for electrodeposition.

Process Parameters:
Solution concentration
Conductivity, pH
Temperature
Current density
Voltage/potential

Deposit Parameters:
Composition/purity
Thickness uniformity
Smoothness, brightness
Hardness, ductility, strength
Grain size

The electroplater needs a rapid and convenient test method to give a good, not necessarily precise, indication of this interaction and, in particular, to indicate any departure from perceived optimum process conditions and then provide the means of correcting that departure. A number of cells have been devised to give such a convenient link. They attempt to correlate the parameters of prime concern—composition and current density—with deposit thickness and thickness distribution. Figure 1 and Table I illustrate this choice.

Some of the cells in Fig. 1 and Table I have very specific applications, e.g., D and K for chromium plating, where the throwing power (TP) is poor and the CrO_3:SO_4 catalyst ratio is critical. Two (B,F) have been adopted for wider use on account of their versatility.

HARING-BLUM CELL

This cell was devised as a TP cell and consists of a long, narrow plating box with one central movable anode and two cathodes placed at relative distances, typically of 5:1 from the anode. TP is calculated from a formula, the classic Haring version being:

Table I. Design and Function of Plating Cells Shown in Fig. 1

Example	*Design*	*Purpose*
C,D	Bent cathode cells	Throwing power and recess plating
A,B,I	Hull cells	Current distribution and deposit appearance
J,K	Slot cells	Slot acts as a point anode
F	Haring-Blum cell	Throwing power (TP) and TP index determination
A,C,E,F,G	Variable geometry	Combined cells
H	Current efficiency cell	Uniform deposition for cathode current efficiency measurement

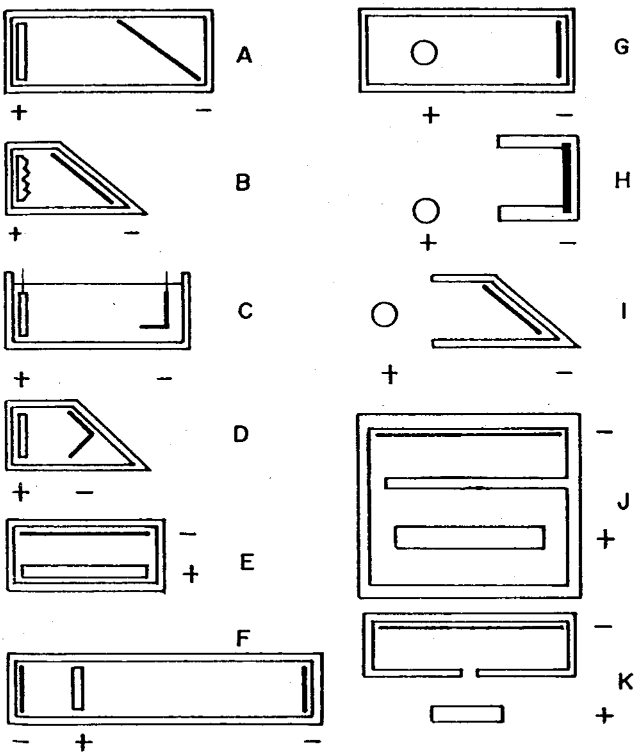


Fig. 1. Test cells used in electroplating control.

$$\% \text{ TP} = 100\ (\text{L}-\text{R})/\text{L}$$

where L is the far-to-near cathode distance ratio and R is the ratio of weights of deposits on the cathodes.

The experimental principle is well established, but a number of alternative formulas have been used primarily to either give a symmetrical TP scale or to expand the scale at specific ranges. Three other TP index formulas in use are

Heatley:

$$\% \text{ TP} = 100\ (\text{L}-\text{M}/(\text{L}-1)$$

Field:

$$\% \text{ TP} = 100\ (\text{L}-\text{M}/(\text{L}+\text{M}-2)$$

Subramanian:

$$\% \text{ TP} = 100\ (\text{L}-\text{M})/\text{M}(\text{L}-1)$$

Of these formulas, that of Field has been most widely used and is incorporated in some standards (e.g., British Standard 205 part 5), with L = 5:1, largely because the values of TPcan vary from +100 to −100, with a value of TP = 0 when the current and metal distribution are equal. This scale gives the poorest TP of −100% (as $M \rightarrow \infty$ when there is no metal

Table II. Throwing Power Indices for Various Values of M

M	*Haring-Blum*	*Heatley*	*Field*	*Subramanian*
1	80	100	100	100
2	60	75	60	37.5
3	40	50	33.3	16.7
5	0	0	0	0
10	−100	−125	−38.5	−12.5
100	−1,900	−2,375	−92	−23.75
∞	−∞	−∞	−100	−25

deposited on the far cathode) and the best TP of +100% (for M = 1). If metal distributes according to the length ratio (e.g., M = 5 when L = 1), the TP is 0. Values of the TP index for each formula are tabulated in Table II for the Haring-Blum cell and several others.

Chin has proposed a logarithmic index, such that M = 1 when L = 1, which would yield more convenient numbers for the index values. Chin's definition is:

$$\text{Logarithmic TP} = \text{Log L/Log M}$$

Graphic and computerized methods have also been developed.

HULL CELL

The Hull cell provides four basic facilities for the electroplater in plating process control: optimization for current density range; optimization of additive concentration; recognition of impurity effects; and indications of macro-throwing power capability.

The common type of Hull cell is the 267-ml trapezoidal container utilizing a 4-in. (10.2-cm) cathode panel inclined at 38° to the parallel sides and having a 2-in. (5.1-cm) anode, which may be corrugated to increase its electrode area. A solution depth of 2 in. (5.1 cm) gives a volume of 267 ml; a 3-in. (7.6-cm) depth would give a volume of 320 ml. Figure 2 illustrates the form of the standard cell. The dimensions are important to give the following relationships:

267-ml cell: 2 g addition is equivalent to 1 oz per U.S. gal
320-ml cell: 2 g addition is equivalent to 2 oz per Imperial gal

The cell can be made of a number of materials, including Perspex, Lucite, polypropylene, or glazed porcelain, depending upon the temperature of usage and the corrosivity of the electrolyte. It is nowadays usual to supply them as a plain box with incorporated air bubbler or with incorporated thermostatic heater.

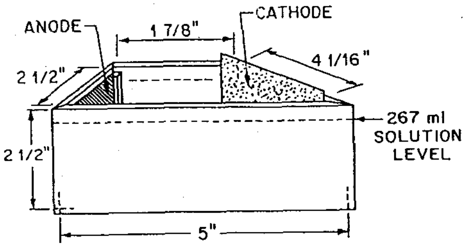


Fig. 2. Dimensions of the Hull cell.

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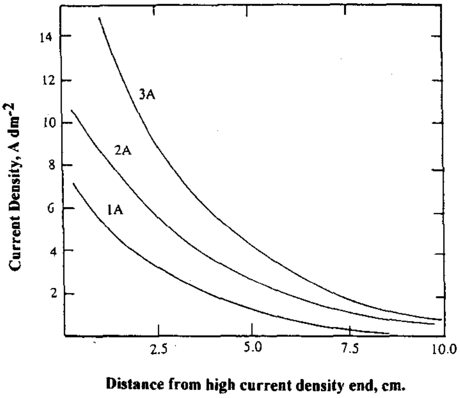

Fig. 3. Calibration graph for a Hull cell with cell currents of 1, 2, and 3 A.

The standard cell current is 2 A, which gives a current density range of 2.4–84 A/ft^2 (0.26–9 A/dm^2) corresponding to anode-to-cathode spacings of 5 to 1⅞ in., respectively. The cell is calibrated by using thickness profiles of the cathode panel and assuming appropriate current efficiencies, such data yielding a calibration graph having curves for 1, 2, 3, etc.-A cell currents (see Fig. 3). If preferred, a formula may be derived having the following form:

$$i_{(L)} = I_{appl}\,(a-b\log L)$$

where $i_{(L)}$ is the current density at a distance L; I_{appl} is the total cell current employed; L is the length along the panel; and a,b are constants requiring calibration. Using inch and A/ft^2 units, $a = 27.7$ and $b = 48.7$; if cm and A/cm^2 are used, $a = 5.10$ and $b = 5.24$.

Other sizes of Hull cell, which have been employed for specific purposes and calibrations, would be:

3 × 5-in. panel with 2.5-in solution depth $a = 18.8$; $b = 28.3$

6.4 × 10.2-cm panel with 5-cm solution depth $a = 5.10$; $b = 5.24$

In all cases, extremities of the cathode panel should be neglected and every attempt made to eliminate solution impurities, residues, etc. and to maintain a consistent procedure with a standard time of plating, typically 2 or 5 min (for 5 and 2 A, respectively). Means of temperature and agitation control can be built in for the same reason.

Interpretation of the cathode panels relates to three pieces of derived information.

1. Establishment of the optimum plating current density range by means of the graph, formula, or various charts. For this purpose, a mid-height line should be taken to minimize stagnation effects at the cell bottom and to avoid emphasizing convection effects at the top meniscus.
2. Establishment of the additive level required to create bright or level deposit zones preferably at the center of the panel. For this purpose, aliquots of 0.5 or 1.0 g are added to the cell, mixed in, and the effect noted.
3. Recognition of atypical appearances attributable to the presence of impurities in solution or to additive degradation products. Experience frequently indicates an appropriate remedy and suppliers of proprietary processes should provide guidance notes.

A number of coding and diagrammatic systems have been used for the panel's appearances (see Fig. 4). The panel demonstrates, in zones from left to right, high-, medium-, and low-current density appearances corresponding to burned/nodular, semibright/bright/leveled to dull, or no

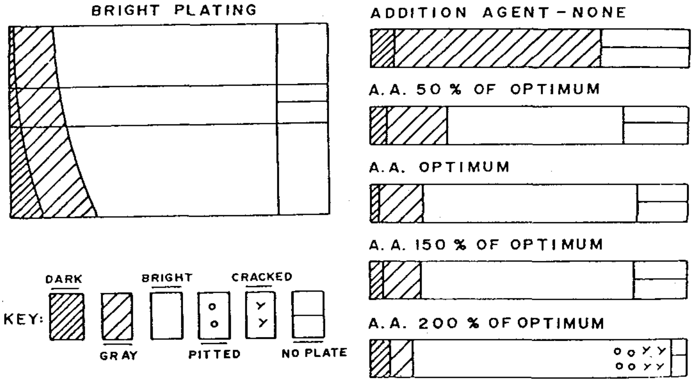

Fig. 4. Diagrammatic system for reporting Hull cell behavior.

deposit zones. The presence of additives will eliminate extremes of burning and powdery/dendritic deposit formation and ideally widen the leveled/bright zone into a practicable working range of current density at that temperature and solution concentration.

MODIFIED CELLS

Each of the basic cells has a number of limitations that have been recognized, but which do not detract from usage as "qualitative procedures to provide quantitative information," however, in a number of specific cases, the limitation could be more serious; for example, temperature control may be poor and metal ion concentrations may change if the test extends over a few minutes. Various modifications have, therefore, been employed, which, for the Hull cell, can be enumerated as in Table III.

The most serious shortcoming relates to the use of agitation to enhance deposition rates in high-speed electrodeposition processes when a correlation factor of 5 to 50 times may apply between the "static" Hull cell and the "dynamic" plating tanks. This factor can be determined typically by comparing bright plating ranges for the Hull cell with those identified for the tank; recently, however, several proposals have been made for current density distribution cells incorporating electrode rotation as a convenient means of quantitative agitation. They utilize rotating cone electrodes; rotating cylinder electrodes; or rotating electrodes in baffled cells.

Table III. Modifications to the Hull Cell

Design	*Authors*
Hanging cell to be suspended in a tank	Mohler[1] Skwirzynski and Huttley[2]
Flat cathode but curved anode to yield a linear current density to L relationship	Gilmont and Walton[3]
Circulating electrolyte pumped along cathode plate at controlled velocity	Dimon[4]
Nonvertical cathode to counter natural convection	Esih[5]
Segment of a concentric cell with cathodes at either end and variably positioned anode	Teraikado and Negasaka[6]

In general, all appear to be reasonably effective, but each requires development work in the context of a particular application to establish its credibility.

TEST CELLS AND TROUBLESHOOTING

A number of applications for test cells have been identified, which may conveniently be classified as *troubleshooting*. In most cases, the most successful use of the cells is when the solutions or processes in question have been fully characterized when known to be in a first-class working order. This clearly suggests that each solution should be fully studied when first used and a set of reference panels and data prepared for regular use. (It is usually advisable to lacquer such panels or otherwise protect them in sealed polymer envelopes in order to provide adequate shelf life.) It is also worth noting that each metal and solution type has its own character, which experience will define only too well.

The test cells, particularly the Hull cell, can be used to identify noncharacteristic behavior under several categories.

1. Establishment of the optimum current density range.
2. Recognition of the effect of variation of temperature, pH, presence of impurities, changes in solution concentration, especially critical components such as conductivity salts or catalysts in hexavalent chromium solutions.
3. Defining the level of brighteners and their breakdown products. This will indicate the need for activated carbon/filtration treatment and the need for brightener replenishment.
4. The effects of agitation must be carefully noted because they may be related to shortcomings of the cell itself.

Cells may also be adapted for other purposes. For example, it need not be necessary to have both a Hull cell and a Haring-Blum cell in regular use, because several workers have shown how TP can be measured using the Hull cell by measuring deposit thickness across the regular panels. In particular, Watson[7] and more recently Monev and Dobre[8] have obtained good comparable data.

Acknowledgment

This chapter has drawn on some aspects of a similarly titled article by J.B. Mohler included in earlier editions of the *Metal Finishing Guidebook.* Readers requiring more information may care to refer to those volumes.

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pH AND ORP

by Michael Banhidi

Consultant, Leonia, N.J.

pH

The term "pH" is used to express the degree of acidity or alkalinity of a solution. Although many different ions may be formed in solution those that establish whether the solution is acid or alkaline are the hydrogen (H^+) and the hydroxyl (OH) ions, respectively. When the hydrogen ions exceed the hydroxyl ions in number, the solution is acid. When they are equal, the solution is neutral. Alkalinity (or basicity) denotes that the hydroxyl ions exceed the hydrogen ions.

Acids and alkalis vary in the degree to which they form ions in solution. Those that almost completely ionize are called strong acids or bases. Hydrochloric acid and sodium hydroxide are examples. Other acids and bases ionize to only a small degree and are called weak acids or bases. Acetic acid and ammonium hydroxide are typical examples. Acids and bases may also be classified according to the number of H^+ ions they can donate per molecule. If an acid can donate only one H^+ ion it is known as monofunctional. If the available H^+ ions are more than one a di- (two) or tri- (three) classification is used.

Even pure water dissociates to a minute degree into hydrogen and hydroxyl ions. Pure water at 25°C always contains 0.0000007 or, in simple form, 1×10^{-7} gram-equivalents per liter of hydrogen ions and, since pure water is neutral, an equal concentration of hydroxyl ions.

The product of these concentrations is a constant equal to 1.0×10^{-14} at 25°C. Thus, if the hydrogen-ion concentration of a solution were 1.0×10^{-4} gram-equivalents per liter, the hydroxyl-ion concentration would be equal to 1×10^{-10} gram-equivalents per liter. Because, in this case, the hydrogen-ion concentration is greater than the hydroxyl-ion concentration, the solution is acidic.

To express hydrogen-ion concentration more conveniently than by the use of decimals or by negative exponents, the term "pH" was adopted. Expressed mathematically, pH is equal to the negative logarithm to the base of 10 of the hydrogen-ion concentration. This is expressed as follows: hydrogen-ion concentration = 1×10^{-7} gram-equivalents of hydrogen ion per liter or has a pH value of 7. Since acid solutions contain more than 1×10^{-7} gram-equivalents of hydrogen ion per liter, the pH values of these solutions are less than 7. Conversely, alkaline solutions have pH values greater than 7.

It is also helpful to remember that a unit change in pH represents a tenfold change in acidity or alkalinity. Thus, compared with a solution of 5 pH, a solution of 4 pH is ten times as acidic—of 3 pH, a hundred times as acidic—and 2 pH, a thousand times as acidic.

The commonly accepted range within which pH values are expressed covers the scale 0 to 14. In plating solutions pH determinations below 1 and above 12 are of little or no value. Outside these limits acidities or alkalinities are more conveniently expressed as percent concentrations.

Nonaqueous solvents may provide a pH outside the 0 to 14 range normally encountered in aqueous solutions. Many digital meters are capable of -19.99 to +19.99 pH. In other meters, such as the analog meters, the scale is limited. In this case the millivolt range of the pH meter provides greater range, such as ±1,400 mV, than the normal 0 to 14 pH range, which is ±421 mV at 25°C; therefore, the pH value can be calculated by comparing the millivolt values obtained in a sample. Of course there is reduced readability with the larger millivolt range. Relating pH and millivolt values observed on the pH meter, the pH value can be calculated using the following formula:

$$pH_x = pH_s - (E_x - E_s)/S$$

Table I. Components of Common Buffers

Components	*Concentration*		*pH*
Hydrochloric acid	0.365g/L	1:1mixture	2.08
Potassium chloride	6.7 g/L		
Potassium hydrogen tartrate	5.64 g/L		3.57
Potassium hydrogen phthalate	10.2 g/L		4.00
Acetic acid	6.0 g/L	1:1mixture	6.9
Sodium acetate	8.2 g/L		
Borax	19.06 g/L		9.2

where pH_x is the pH of the sample (x); pH_s is the pH of the standard (s); E_x is the millivolt value of the sample as read by the pH meter; E_s is the millivolt value of the standard as read by the pH meter; and S is the slope, normally 59.16 mV/pH unit at 25°C. The pH can be determined colorimetrically or electrometrically.

Colorimetric Method

For a visual indication of the pH a so-called acid-base indicator or mixture of indicators is employed. Such an indicator is a weak organic acid (or base) having the special feature that it changes color within a definite pH range.

The standard colorimetric method is carried out by placing a given quantity of solution to be tested in a glass tube. A set amount of indicator is added and compared with standards, in which a solution with known pH has been prepared with the same amount of indicator. This method is cumbersome and rarely used today.

The derivative of the standard colorimetric method is the pH test paper. The indicator is impregnated on an absorbent paper strip. A color chart with the appropriate pH values is printed on the strip or a card. After immersion in the solution the strip is compared with the standard color. Reliable pH papers are accurate ±0.3 units from the electrometric value. In the case of a strong oxidizing or reducing solution the pH papers are not reliable.

Electrometric Method

Certain electrodes, such as hydrogen, quinhydron, antimony and others, when immersed in a solution, develop voltages (called electrical potential), which depend upon the pH of the solution. As a result a pH meter is basically a millivolt meter. The glass bulb electrode is the key to making a pH measurement. The special composition glass used is very selective and sensitive to hydrogen ions. The potential that is developed at the glass membrane can be related to the pH of the solution. To complete the circuit and provide a stable and reproducible referencing potential, another electrode is required. The "reference" electrode makes contact with the solution through a junction, which allows slow leakage of the filling solution into the sample. When the glass (pH) and reference electrodes are paired, or built together as a combination electrode, and connected to a pH meter, the voltage developed at the electrode pair is amplified and displayed on a meter or a digital readout. The meter is standardized with a known solution called a buffer. A buffer is a specially prepared solution that resists changes in pH and has a specific pH value at a specific temperature. In Table I the component of the most common buffers is shown.

When highly accurate pH measurements are required, temperature, meter standardization, and electrode technique should be considered. Temperature has two effects on the accuracy of pH readings. The first effect is on the electrodes, which is corrected by either automatic temperature compensation (ATC) or by manually adjusting the temperature control on the pH meter. Temperature also effects the pH value of the buffer (which is used for standardization). Because samples do not change pH with temperature in the same way, the

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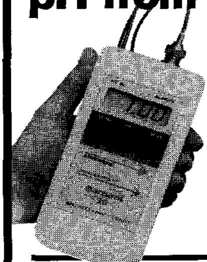

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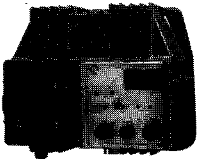

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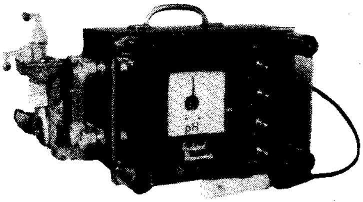

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Table II. Standard Potential (E^0)

Electrode Reaction	*E^0 (V)*
$Na^+ + e^- = Na$	-2.714
$CNO^- + H_2O + 2e^- = CN^- + 2OH^-$	-0.97
$Zn^{2+} + 2e^- = Zn$	-0.763
$2H^+ + 2e^- = H_2$	0.000
Ag/AgCl electrode, 4N KCl	+0.199
Calomel electrode, sat KCl	+0.244
$(Cr_2O_7)^{2-} + 14H^+ + 6e^- = 2Cr^{3+} + 7H_2O$	+1.33

relationship between temperature and pH must be determined experimentally. Most buffer bottles have a chart on their labels that gives the pH as a function of temperature.

The pH meter should be standardized with accurate buffers, which have pH values close to the pH values of the samples. Use of the slope control corrects for nonideal electrode behavior associated with aging of the electrodes.

Proper storage of the electrodes increases their life and provides faster response and less drift when making pH measurements. The electrodes should be carefully rinsed between each measurement to prevent contamination. Do not wipe the glass electrode, which could transfer a charge to the glass bulb resulting in a long stabilization time. The rinsed glass electrode should be stored in distilled water. Finally, the consistency of the measuring technique is important, whether the samples are measured in static or stirred condition; however, the standardization buffer and the sample solution should be treated the same.

OXIDATION-REDUCTION POTENTIAL

Oxidation-reduction potential (ORP) measurements are used to monitor chemical reactions, quantify ion activity, or determine the oxidizing or reducing properties of solutions. Although ORP measurements are somewhat similar to those of pH, the potential value must be interpreted carefully for useful results. An ORP measurement is made using the millivolt mode of the pH meter. Consequently, by substituting a metallic electrode for the pH glass electrode, many other ions besides the hydrogen ion can be detected with the same pH meter.

In many chemical reactions electrons are transferred from one substance to another. By definition a substance gains electrons in a reduction reaction and loses electrons in an oxidation reaction. Oxidation and reduction reactions occur together. The available electrons from an oxidized substance are taken up by the reduced substance until an equilibrium condition is reached.

Since it is impossible to measure absolute potentials, an arbitrary standard, the hydrogen electrode, is chosen. ORPs are defined relative to this standard. The electrode reaction

$$2H^+ + 2e^- = H_2$$

is assigned a potential of 0.000 V when the hydrogen activity is 1 M (concentration of 1 mole/L), and the partial pressure of hydrogen is 1 atm.

When reactions are written as oxidation (e.g., $Na = Na^+ + e^-$), potentials have the opposite polarity. The standard potential E^0 of any oxidation-reduction reaction is referenced to the standard hydrogen electrode and refers to the condition of the oxidation-reduction reaction where temperature is 25°C, ion activity is unity, and gases are at 1 atm pressure. Table II shows the standard potential E^0 associated with various reactions.

The ORP is characteristic of reactions involving both oxidation and reduction and varies as a function of (1) the standard potential, (2) relative ion concentration, (3) temperature, and (4) the number of electrons transferred in the reactions.

ORPs are usually displayed as millivolts (mV). When measured with a pH meter (set to read in mV), this ORP is generally the electromotive force (EMF) difference developed between the ORP electrode and a constant voltage reference electrode (saturated calomel, instead of a normal hydrogen electrode) that is immersed in the solution. Any one of three different types of metallic electrodes may be used. There are three types of metallic electrodes used in ORP measurements that differ in construction but are based on the same principle that an oxidized and a reduced state must be present.

The first type of metallic electrode to be considered consists of a metal contact with a solution of its own ion. The metallic electrode is in a reduced state and its ions are in an oxidized state. An example of this type is silver in a silver nitrate solution. It is used mainly on the analytical field.

The second type of metallic electrode consists of a metal coated with a sparingly soluble salt of this metal in a solution of soluble salt with the same anion (e.g., silver-silver chloride in a solution of potassium chloride). The third type of metallic electrode consists of an inert metal in contact with a solution containing both the reduced and oxidized state of an oxidation-reduction system. An example would be platinum in contact with ferric-ferrous ions. Platinum and gold are the most common ORP electrodes.

The nature of the test solution and the method to be used will determine the choice of the electrode. The reference electrodes can be identical, but a noble metal electrode replaces the glass pH electrode. The signal from the ORP electrodes must be fed into an amplifier with high-input resistance.

If one or both reactions pair hydrogen ions the ORP measurement becomes pH dependent. Consider the following reaction, which occurs in the reduction of hexavalent chromium:

$$Cr_2O_{7^{2-}} + 14H^+ + 6e^- = 2Cr^{3+} + 7H_2O$$

The reaction depends on solution pH. Potential changes measured by the ORP electrode will continue to vary with the redox ratio, but the absolute potential will also vary with pH. In the first step the pH is lowered to 2 to 2.5. Sulfur dioxide or sodium sulfite solution is used as the reductant. The overall reaction is

$$Cr_2O_7^{2-} + 2H^+ + 3H_2SO_3 = 2Cr^{3+} + 4H_2O + 3SO_4^{2-}$$

In the second part of the process the waste liquors are neutralized to a pH level of 7 to 8. At this pH the chromic ion precipitates as a sludge and is sent to clarifiers for ultimate disposal or recovery. All these reactions will take place in a definite pH and in a specific millivolt range.

Although applications for ORP measurement are not as widespread as for pH one of the most important applications in the metal-finishing industry is the oxidation of cyanide wastes. Oxidation converts the toxic cyanides to harmless compounds. Typically, chlorine gas or sodium hypochlorite are the oxidants. In the first step caustic or lime is added to make the cyanide-bearing waste alkaline to a pH of 9 to 10. An acid solution would release deadly cyanide gas; therefore, the system generally incorporates pH control. The first stage reactions are

$$Cl_2 + CN^- + 2OH^- = 2Cl^- + OCN^- + H_2O$$

The second step in cyanide oxidation takes place at a controlled pH in the 7 to 8 range. The reaction is:

$$3Cl_2 + 2OCN^- + 4OH^- = 6Cl^- + 2CO_2 + N_2 + 2H_2O$$

In industrial plants ORP is rarely applied to nice clean reactions where potentials can be estimated easily. In waste treatment or sewage plants, for instance, solutions contain a host of constituents that the reagent oxidizes and reduces simultaneously. ORP relates to the concentrations and activities of all participating reactions. It frequently becomes necessary to determine the control points experimentally.

Table III. ORP Values of Quinhydrone-Buffer Standards

	pH 4			*pH 7*		
	20°C	*25°C*	*30°C*	*20°C*	*25°C*	*30°C*
Reference						
Ag/AgCl	+268	+263	+258	+92	+86	+79
Calomel	+233	+218	+213	+47	+41	+34

If day-to-day relative potential values are to be compared, the pH meter must be standardized to the same starting point. Short the meter glass and reference inputs and adjust the standardization control until zero millivolt is displayed using the "absolute millivolt" mode to set the potential to some arbitrary value when the electrodes are reading the potential in a repeatable standard solution.

Because ORP is a characteristic measure of redox equilibrium it should not require standardization or calibration. The measured potential is absolute in a sense. Yet, frequently, it is desirable to check systems for proper operation and electrode poisoning. Solutions of known potential can be developed by saturating buffer solutions with quinhydrone. The reaction is such that the measured potential will vary only along with the solution pH and temperature. The procedure is as follows: (1) Saturate the buffer with quinhydrone, made up fresh for each test. Quinhydrone is not readily soluble so a few crystals stirred into the buffer are sufficient. The solution will be amber colored. (2) Clean the platinum electrode. (3) Place the platinum and reference electrodes in a quinhydrone-buffer solution and measure the potential and temperature. Measured potential will generally be within ±10 mV of theoretical value. The ORP values of quinhydrone-buffer solution can be seen in Table III.

IDENTIFICATION OF DEPOSITS

by Charles Rosenstein
AMZA Ltd., Holon, Israel

and Stanley Hirsch
Leeam Consultants Ltd., New Rochelle, N.Y.

Unknown metal deposits are qualitatively determined by systematic spot testing (Table I) or by instrumental analysis. Before testing, lacquer and other protective coatings must be removed from parts with a suitable solvent. Dirty parts are cleaned with a paste made from ordinary kitchen cleansers and water, and are then rinsed well with water.

SPOT TESTING OF DEPOSITS

Immerse the part in warm 50% by volume nitric acid. If the surface is attacked, note the color of the nitric acid solution and proceed to Table II. For thin deposits, the initial reaction of nitric acid on the deposit must be carefully observed, so that the deposit will be tested and not the base metal. When gold is thinly plated on brass and then placed in a nitric acid

Table I. Flow Chart for Systematic Spot Testing of Deposits

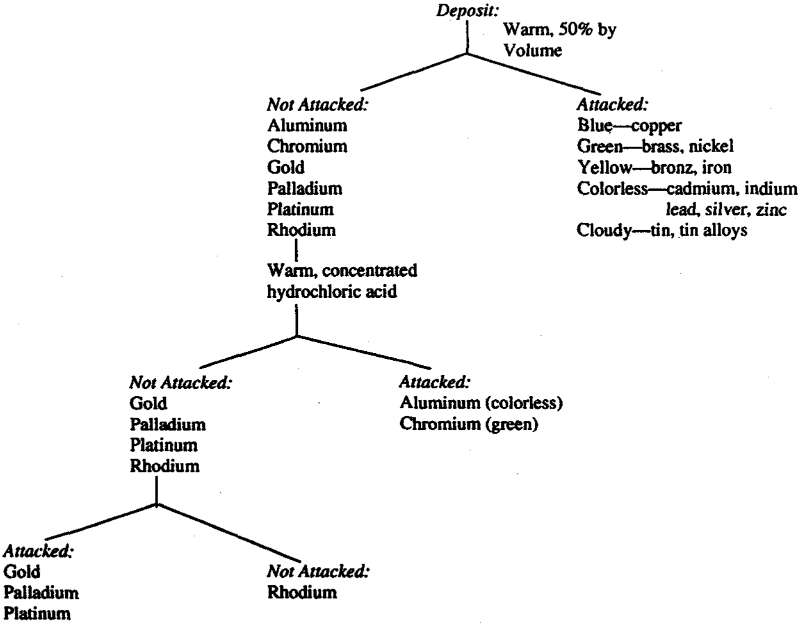

Table II. Deposits Attacked by 50% by Volume Nitric Acid

Color of Nitric Acid Solution	*Qualitative Test to Confirm Deposit*
Colored: Blue—copper Green—brass, nickel Yellow—bronze, iron	Dissolve the deposit in warm 50% by volume nitric acid. A blue solution indicates copper.
	A yellow nitric acid solution indicates bronze or iron. Add ammonia until red litmus turns blue. A reddish-brown precipitate indicates iron. If iron is not present, the deposit is bronze.
	A green nitric acid solution indicates brass or nickel. Add ammonia until red litmus turns blue. Then add five drops 5% dimethylglyoxime in ethanol. A red precipitate indicates nickel. If nickel is not present, the deposit is brass.
	Copper and copper alloys are confirmed by adding ammonia to a nitric acid solution until red litmus turns blue. Then add five drops 5% benzoinoxime in ethanol. A green precipitate indicates copper or a copper alloy.
Colorless: Cadmium, indium, lead, silver, zinc	Dissolve the deposit in warm 50% by volume nitric acid. Add one drop concentrated hydrochloric acid. A cloudy solutionindicates silver.
	If silver is not present, add one drop concentrated sulfuric acid to the nitric acid solution. A white precipitate indicates lead.
	If lead is not present, add ammonia to the nitric acid solution until red litmus turns blue. A white precipitate indicates indium.
	If indium is not present, add ammonia to the nitric acid solution until red litmus turns blue. Then add 10 drops 10% sodium sulfide solution. A yellow precipitate indicates cadmium; a white precipitate indicates zinc.
Cloudy: Tin, tin alloys	Dissolve the deposit in warm 50% by volume nitric acid. Add water, filter the solution, and note the color of the filtrate: copper and nickel alloys are blue-green; zinc and lead alloys are colorless. Confirm the constituent of the tin alloy by testing the filtrate with the above specific tests for copper, lead, nickel, and zinc.

solution, the brass will be attacked and insoluble gold flakes will be present in the solution. Specific qualitative tests in Table II confirm the type of deposit.

If the surface is not attacked by warm 50% by volume nitric acid, proceed to Table III. Place 10 drops of warm concentrated hydrochloric acid on the part. If the deposit is attacked, it is either aluminum (colorless) or chromium (green). If the deposit is not attacked, place two drops aqua regia (250 ml nitric acid and 750 ml hydrochloric acid per liter) on it and check if the deposit dissolves. Each of the specific qualitative tests for gold, platinum, and palladium (Table III) must be run to determine the type of deposit. Known coatings may be tested along with unknown ones in order to become familiar with the reactions and colors of a particular test.

Table III. Deposits Not Attacked by 50% by Volume Nitric Acid

Deposit	*Ten Drops Warm Concentrated HCl*	*Two Drops Aqua Regia*	*Qualitative Test to Confirm Deposit*
Rhodium	Not attacked	Not attacked	
Aluminum	Attacked (colorless)		
Chromium	Attacked (green)		
Gold Palladium Platinum	Not attacked	Attacked	Dissolve the deposit in aqua regia. Evaporate the solution to dryness, add 20 ml 10% by volume hydrochloric acid and one ml dimethylglyoxime in ethanol. A yellow precipitate indicates palladium. If palladium is not present, add two grams ammonium chloride to the solution. A yellow precipitate indicates platinum. If platinum is not present, add 10 ml 10% oxalic acid to the solution, heat, filter the precipitate and dry. A gold-colored precipitate indicates gold or a gold alloy.

INSTRUMENTAL ANALYSIS

Several instrumental methods (see chapter elsewhere in this *Guidebook* on chemical analysis of plating solutions) provide a quick and sensitive means of identifying unknown metallic deposits. Deposits are scraped off, filed, or stripped by immersion in a suitable solution.

Emission Spectrometry

Emission spectrometry is useful in the qualitative detection of metals because of its accuracy, speed, and ease of operation. The sample is inserted into a graphite electrode in the form of filings, shavings, or a solution. A DC arc is usually used to excite the sample and cause it to emit a unique and characteristic set of spectral lines.

It is necessary to identify only a few of the most intense lines of each element to confirm conclusively the presence of an element. Likewise, the lack of these lines signifies the absence of that element in the sample. Tables of characteristic wavelengths are available.

An emission spectrograph of pure iron is a wavelength standard, as it labels and identifies the actual wavelengths from the deposit being determined. Spectra of the pure iron and other pure metals are photographed side by side with the spectrum of the sample.

X-Ray Fluorescence

When a sample is exposed to X-rays of certain wavelengths, the various elements in the sample will give off more X-rays whose energies are characteristic of the elements in the sample. Qualitative analysis of these elements is performed by measuring the energies of these fluorescent X-rays.

Mass Spectrometry

A mass spectrometer separates ions from an ionized sample according to their mass-to-charge ratios. Qualitative identification is obtained from these ratios.

Polarography

The half-wave potential in polarograms is characteristic of the substance undergoing reduction at the microelectrode (dropping mercury electrode).

Atomic Absorption Spectroscopy

Almost all metals can be analyzed by atomic absorption spectroscopy. Small amounts of an unknown deposit are needed for identification and different current density areas can be analyzed. Extensive sample pretreatment is unnecessary.

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SURFACE TENSION

by Norbert Sajdera

Kocour Co., Chicago

Surface tension is defined as a cohesive molecular force acting on the surface of all liquids, which tends to force the solution to its smallest volume. Due to this force, the surface of the liquid becomes an elasticlike film that exerts its force perpendicular to the surface of the solution (if viewed from inside the liquid, a force pulling inward at the surface). A liquid with a high surface tension can, therefore, form a larger volume than a liquid with a low surface tension.

The dyne/cm is the unit used for measurement of surface tension. This represents a force of 1 dyne acting perpendicularly on a segment of the surface 1-cm long. The value for water has been measured accurately and is accepted to be 72.75 ± 0.05 dyne/cm at 20°C.

When a sheet of metal is immersed in a liquid and then removed, a layer of liquid clings to the surface of the sheet. This layer will hold more liquid when the surface tension is high than when the surface tension is low; therefore, a solution that has a low surface tension becomes easier to rinse because it has less solution on it. This property is valuable when implementing control of alkaline cleaners and acid dips. The proper control of the surface tension will reduce drag-out and facilitate rinsing between process solutions.

When surfactants (surface-active agents) are used to reduce surface tension, occasionally more than one benefit can be achieved. For instance, in some nickel and zinc plating solution formulations, the surfactant's primary function is as an antipitting agent; however, the reduction of surface tension on the cathode surface also tends to enhance the effect of other additives on the character of the electrodeposit. In many cases, the analysis of the surfactant is complex and the simplest control is the measurement of the surface tension.

In the case of chromium plating solutions, the sole purpose of the surfactant is to suppress the emission of the chromium mist produced during operation of the solution. Close control is required because the surfactant is destroyed by the chromic acid and removed by drag-out.

Many methods have been used to measure the surface tension of liquids. The *capillary method* seems to be the most convenient. The procedure requires immersing one end of a small diameter (<1 mm) capillary into the liquid. The liquid will then rise up the capillary due to the surface tension of the liquid. The height reached in the capillary can be used to measure the surface tension from the formula:

$$\text{Surface tension} = h\ r\ d\ g\ /2$$

where: h = height in centimeters; r = capillary radius in centimeters; d = density of liquid, g/cm^3; and g = gravitational constant, cm/sec^2.

This method has been used to measure the surface tension of pure liquids very accurately; however, the addition of surfactants introduces problems such as bubbles in the column, difficulty in measuring the lower height rise caused by the decreasing surface tension, and problems with cleaning fine capillaries. Because of these problems, this method has not been widely used by electroplaters.

The surface tension of a liquid influences the size of the drop that will be formed when the liquid is suspended from a glass tip. This fact has been used to devise various different *drop-weight methods*. Surface tension can be calculated very accurately from the relationship:

$$\text{Surface tension} = mg/rXF$$

where m is the mass of a slowly formed drop, which falls from the horizontal tip of a polished capillary tube due to acceleration force g and whose outside diameter is 2r. F is a function of V/r^3.

The mass and volume (V) are measured from the accumulation of 30 or more drops. F is obtained from Volume 4 of the *International Critical Tables* (p. 435). With careful measurement, the method is capable of ±0.1% accuracy.

The drop-weight method is also the basis for the stalagmometer. The *stalagmometer* is a modification of a pipette that permits a more controlled formation of the drops. There are two points etched on the stem of the stalagmometer that contain a definite volume of liquid. Below this calibrated volume, a capillary is inserted to control the speed of drop formation and the bottom tip is formed into a larger diameter that is polished flat. The test is performed by filling the stalagmometer with the test liquid and allowing the liquid to slowly form drops. The operator counts the number of drops that form and fall as the top of the solution moves from the upper to the lower etched point. This method does not directly measure the surface tension, but compares the number of drops of the test liquid to the number of drops of pure water formed with this stalagmometer tube. The surface tension is then calculated with the following formula:

$$\text{Surface tension} = \frac{72.75 \times \text{Number of water drops} \times \text{Solution specific gravity}}{\text{Number of solution drops}}$$

This method is widely used by electroplaters because the equipment is inexpensive and precise measurements are easily obtained.

The surface *tensiometer* is a force gauge that uses a torsion spring to apply a pulling force to a platinum-iridium ring. The tensiometer consists of a container to hold the test solution mounted on a table that can be raised and lowered smoothly. The torsion spring has a dial to indicate the force applied to the ring.

The test is performed by lowering the platinum-iridium ring into the test solution, then lowering the solution and adjusting the torsion spring until the rings breaks free from the surface of the solution. Currently, manual and semiautomatic models are available. The semiautomatic model provides more uniform motion for raising and lowering both the test ring and the sample table. This test is sensitive to vibration and requires care in cleaning the sample container and the platinum-iridium ring.

The maximum *bubble pressure method* uses the pressure differential between two probes with unequal orifice diameters. A constant volumetric gas flow is delivered to each probe, and the pressure differential between the probes is measured while bubbles are formed at the orifices, which are submerged in the solution. This pressure is proportional to the surface tension of the solution.

Modern instruments use computers to collect and analyze the pressure data and compute the surface tension. Although this method is used largely in the manufacture of inks, paints, dyes, adhesives, and so on, it is mentioned here because it is the only method available that can be used for automated surface tension control.

The stalagmometer has been used to measure surface tension directly. The greatest use for this method, however, has been for comparing the surface tension of the test liquid to the surface tension of water. Another common use is to estimate the quantity of surfactant in the process solution. This is accomplished by adding known amounts of surfactant to a process solution and measuring the surface tension at each concentration. In the case of the stalagmometer, only the number of drops needs to be plotted.

Surface tension can be measured by several methods. The method chosen depends on the accuracy needed, cost of equipment, time available for testing, and skill of the operator.

MICROHARDNESS TESTING OF PLATED COATINGS

by John D. “Jack” Horner

Consultant, Milford, Mich.

Hardness has been defined simply as the resistance to penetration. In order to measure this resistance to penetration a testing machine is used to push a specific indenter into the test material with a specified force, and either the depth of penetration or the area of the “footprint” left by the indenter is used to derive a hardness “number.” Hardness as measured by indentation is not a single fundamental property but a combination of properties, and the contribution of each to the hardness number varies with the material and the type of test. Variously shaped indenters have been developed and are in use in different industries. The hardness number varies with the size and shape of the indenter and the force used, among other variables, which results in several different hardness scales. The metalworking industry uses several with one or more of the many Rockwell scales being among the more common. Unless the coatings are extremely thick Rockwell methods cannot be used for plated parts.

The results of hardness testing of plated coatings have been the subject of disagreements for several years. Standardized methods such as ASTM E 384 (Standard Test Method for Microhardness of Materials), which had been developed to measure the hardness of solid materials, were found to need certain modifications to be adapted to relatively thinly plated coatings. This problem was recognized with ASTM B 578 (Standard Test Method for Microhardness of Electroplated Coatings). The term microhardness is used to describe hardness as measured with small indenters and comparatively lower forces. (Some have proposed that microhardness would be more accurately described as microindentation.) Generally, the term microhardness is used for hardness testing when the forced used is 1,000 grams or less.

WHICH HARDNESS SCALE TO USE

There are two indenters commonly used for testing plated coatings. The Vickers indenter has been in use longer and is a small, pyramid-shaped diamond that produces a square footprint or impression. The Knoop indenter was developed by the National Institute of Standards and Technology (NIST) and is a small, rhomboid diamond that produces a longer, thinner, less-penetrating impression. This feature makes it more adaptable for thinly plated coatings. Currently, the ASTM specification specific for microhardness testing of plated coatings is B 578 and covers only the Knoop indenter. It is expected that future revisions of this specification would include the Vickers indenter. It is important to know that these two indenters are not the same and microhardness numbers, although fairly close, are not interchangeable. There are some advantages to using each method. Generally, Knoop is preferred for thinner coatings because of its narrower indent and because it penetrates only about one-half as deep as the Vickers indenter. The Vickers indenter is reported to be more tolerant of slight surface irregularities. Modern testing machines permit the use of either indenter. If necessary to cite an ASTM Standard Test Method the Knoop indenter has the advantage currently.

WHAT LOAD (FORCE) TO USE

It is important to recognize that microhardness numbers can vary with the force used. This is more pronounced at the lower forces. For the harder plated metals, such as hard copper, nickel, or chromium, 100-gram force (0.981 N) should be used. Higher loads of

200-gram force generally show less variance of readings between operators and laboratories but can produce cracking, not always apparent, with the harder, more brittle deposits. At loads of 50-gram force or less, higher values are obtained with considerably more variance, especially with harder materials. Many specifications recommend against using 50-gram loads with these harder materials. Lower forces of 25-gram force or less should be used only for the softer metals such as gold or lead.

HOW MICROHARDNESS IS EXPRESSED

The correct way to express microhardness is to place the microhardness number first, followed by the term for the scale (indenter) as either HK, for hardness Knoop, or HV, for hardness Vickers, with the force used as a subscript. ASTM B 578 specifies this in grams force. The international ISO 4516 specification expresses the force in kilograms force. Both specifications agree that the system of designation of hardness shall be such that the numerical value of the hardness number remains unaffected by the introduction of the SI unit of force, the newton, in place of the old unit. (The force, in newtons, divided by 0.00981 is equal to gram force.) Thus, a microhardness of 550 using a 100-gram force (0.981 N) and a Knoop indenter should be expressed as 550 HK_{100}.

RECOMMENDED PROCEDURE

Preparation of the Sample

Adequate plate thickness is necessary to achieve good results. Minimum plate thicknesses of 0.002 in. (about 50 mm) are preferred. Using the Knoop indenter an absolute minimum of 0.001 in. (25 mm) is sometimes used, although considered too thin by some. When production parts have insufficient plate thickness, it will be necessary to continue the plating of a sample part under constant conditions until minimum thickness is obtained. The use of test panels plated under the same conditions as the work is a common practice.

Except in rare instances, hardness is measured on a cross-section of the plated part. Cut the sample using adequate cooling to avoid any accidental heat treating of the specimen. Overplate the specimen with another metal to protect the edge and provide a visible contrast; e.g., use copper to overplate nickel or vice versa. The hardness of the overplate should be in the same range of hardness as the plate to be tested. Usually, an overplate thickness of about 0.001 in. (25 mm) is satisfactory. Mount the specimen in a plastic medium suitable for metallographic work. If the hardness of the specimen may be affected by the time at temperature involved in the mounting operation use low-temperature–setting plastics.

Grind and Polish the Mount

Avoid heat and "buffing" or work hardening the surface. Normal metallographic techniques require using successively finer grinding and polishing media, rinsing carefully between steps. The mount is rotated 90° at each step to help keep the surface of the mount flat and parallel with the bottom of the mount. The final finish should show few, if any, scratches when viewed at 400× magnification. The final polishing step is often a fine-grit diamond paste.

Calibrate With a Stage Micrometer

Take several readings and average the results to determine any correction factors that need to be used in measuring the indents on test pieces. Magnification of the testing machine should be a minimum of 400×; higher magnification can be a benefit. This correction factor can be different for different people using the same machine, but it should not change for each individual as long as nothing is changed in the equipment. This calibration should be repeated every few months or whenever there is any reason to expect that there has been a change.

Calibrate by Checking a Standard Test Block

It is preferred that the test block be of the same general hardness as the deposit being tested, within reason. (Avoid using a hard nickel or steel test block when the deposit is to be soft gold.) Standard hardness test blocks are available from various laboratory and testing equipment supply houses. Certified standards for microhardness made from electroformed, hard nickel are available from the NIST Office of Reference Materials (Gaithersburg, MD 20899). Using standard test blocks of the same general material as the deposit may minimize potential errors due to differences in resilient properties possible with some metals. (To verify the testing machine, ASTM E 384 calls for 20 indentations on the standard test block.)

Measure the Microhardness of the Sample

Following the instructions of the testing machine manufacturer, make the indentations with the long axis of the indenter parallel to the test surface when using the Knoop indenter. The Vickers indentation should be placed so that one diagonal is perpendicular to the edge of the coating. Indentations should be made in the center of the deposit and spaced at least about one and one-half times the length of the diagonal from each other. For best results, indentations should be symmetrical. When using the Vickers scale, both diagonals are measured and averaged; each diagonal should be of equal length within 5%. Knoop indentations only require measurement of the long diagonal; however, each leg should be of equal length within 20%. (Less than 20% would be better.)

Report the Results

ASTM B 578 asks that results be based on at least five measurements and that the report include range of hardness units, average (arithmetic mean), estimated standard deviation, and coefficient of variation. ISO 4516 asks that the report include the range, with the average optional, whether the tests were done on the surface or a cross-section, and any deviations from normal conditions such as temperature or force-retention time.

HOW MANY READINGS SHOULD BE TAKEN

ASTM B 578 and ISO 4516 call for "at least five measurements." During an extensive series of round-robin tests done over several years, better results were obtained taking five measurements on each of five indentations. This work was done by a section of Committee BO8 in ASTM. From one series of some 6,500 test readings, covering both Knoop and Vickers indenters, it was found that the total average microhardness readings were very close to the certified readings of NIST, even though some ranges were somewhat broad. It is recommended that given the possible variables in the technique, this practice of taking five measurements of each of five indentations be used. Use this for calibrating the machine with the standard test block and when testing sample deposits.

SOURCES OF ERRORS

Vibration

During the indentation process, while the indenter is in contact with the test part, vibration may be a major factor, often underestimated. The slightest vibration during this period will give low, false readings. Running motors; fans; people walking near the machine; auto, truck, or train traffic nearby; even thunderstorms in the area can cause significant vibration, which affects the microhardness readings. It is important to place the microhardness testing machine in a fashion and location to minimize any vibration effects. The operator should be aware of this sensitivity to vibration and keep his or her motions smooth and maintain minimum movement during the indentation process. At lower test loads vibration is even more critical. ASTM E 384 limits vibration to less than 0.005 g (2 in/sec^2). Slight, sporadic vibration can be a major source of the wide ranges often encountered in microhardness readings.

Equipment Problems

Mechanical: Indentation process must be smooth, with a controlled velocity (slow) of the indenter. Full force should be applied for usually 10 or 15 seconds. Longer load-retention times can be more prone to the effects of vibration. ASTM E 384 contains information on verification and calibration of microhardness testing machines.

Optics: 400× magnification should be the minimum; higher magnification would be better. Electronically projected images are more easily measured. Results obtained with lower magnification have varied widely and not agreed with results at 400× and higher.

Indenters: Should be examined at about 100× periodically for defects. Any chipped indenter must be replaced.

Sample Preparation Problems

Surface not perpendicular to indenter: This results in unsymmetrical indents, which can be corrected by repolishing the mount or by the use of a stage-leveling device.

Excessive surface scratches: These can interfere with locating the exact start of the indentation. Repolish the sample.

Sample overheated or surface work-hardened during preparation: A thin layer of work-hardened material may be removed by repeated light etching and light polishing steps. If the sample has been accidentally heat treated a new sample must be prepared.

Measurement Problems

With a machine properly calibrated against a stage micrometer it has been determined that measurements should not vary more than 5%. The range of hardness numbers, however, increases substantially when testing harder materials (with the widest ranges found with the Vickers indenter), and measurement errors will exceed 5%. With microhardness numbers over about 800 HK_{100}, considerable variance can be expected, and it is often recommended that a practical range be specified, rather than a single figure.

Other Common Errors

Reporting errors: Omitting force (load), not expressing hardness numbers properly, and not including the other data as required by the pertinent specifications.

Converting from one hardness scale to another: Most specifications advise against doing this unless using conversation data actually obtained from the specific material being tested. Hardness numbers should be expressed in the scale that they were tested. Similarly, conversion from one test load to another is to be discouraged without actual data obtained with the same test material.

Measuring hardness of nonuniform deposits: Porous deposits, deposits that contain codeposited hard or soft particles (often termed composites) will produce unreliable readings and should not be tested for hardness in the composite form using microindentation methods.

Deposit too thin: Indentation made too close to the edge of the deposit.

Very brittle deposits: These often crack, which is not always visible, and given unreliable results. The temptation is to use less force, which produces much higher numbers and is not comparable to data obtained at the recommended load of 100-gram force. This is the minimum force required for harder materials by the pertinent hardness specifications.

Including "unusual indentations" in the averages: An indentation that is noticeably different, either in shape or size, from other indentations is probably the result of an unknown test variable and not a true reflection of the hardness and should be rejected.

CONCLUSION

Microhardness testing of plated coatings, or more properly, microindentation test methods for hardness of these materials, can be a good tool in the study of materials, development of improvements, process and quality control, and other applications. The standard test methods, when followed closely and with due attention to the procedures and variables contained therein and in this article can produce dependable and repeatable results within practical limits. In the real world, however, these procedures have not always been followed. The reader is cautioned that there are data in the literature, both old and recent, that are incompletely presented and difficult to duplicate or to compare with data from other sources. The reliability of the test method has been found to improve with the number of indentations and the number of measurements if all the necessary precautions are taken and if the operator is knowledgeable on the procedure and has adequate equipment. It appears inherent to the method that wider ranges are found with the harder materials. Of the two common indenters Knoop has the smaller range when testing the harder materials. Those writing specifications and setting limits on hardness should be well aware of these factors.

FINISHING PLANT ENGINEERING

EQUIPMENT SELECTION, AUTOMATION, AND ENGINEERING FOR PLATING SYSTEMS

by Vincent S. Binsfeld

Unified Equipment Systems Inc., Clinton Township, Mich.

Today's economic climate challenges many plating shops to break even, let alone make a reasonable profit. Rising labor and material costs, plus the shortage of competent plating personnel, are some of the factors compelling shop management to evaluate automation as a means of business survival.

Automation is the practical answer to handling the more complicated plating cycles. New plating treatments and critical time factors call for the production consistency and quality uniformity that automatic equipment offers.

Shop management, wanting to improve profitability, must look open-mindedly at the whole picture. Sound financing must be devised to convert a shop to automatic equipment, which, in turn, promises:

- Increased productivity creates greater efficiency. This increase averages about 20%.
- Increase in general production reliability of automated vs. manual operation.
- Quality control is improved with commensurate lowering of reject rate.
- Reduced consumption of chemicals, with cost savings of 25% commonly obtained.

With these plus factors, benefits vary with the degree of automation since the broad choice of equipment allows almost any degree of mechanization. The plater must ask himself, "Just how far do I want to go in automating the transfer of parts toward, through, and away from the plating operation?"

These transfer steps require only two basic types of automated equipment: return-type automatic and programmed hoist. Both shelf and custom-designed systems, with or without a variety of auxiliary equipment options, are available.

In addition to studying the simple descriptions and comparative investment vs. savings analysis, talking with suppliers is essential. Include suppliers who make several types of automated plating equipment, get the pros and cons of each, and then form an objective opinion of needs for the specific system to be automated.

THE PROGRAMMED HOIST SYSTEM

Among the basic types, the programmed hoist is available for horizontal barrel work or for rack and basket work. Major advantages of the hoist are:

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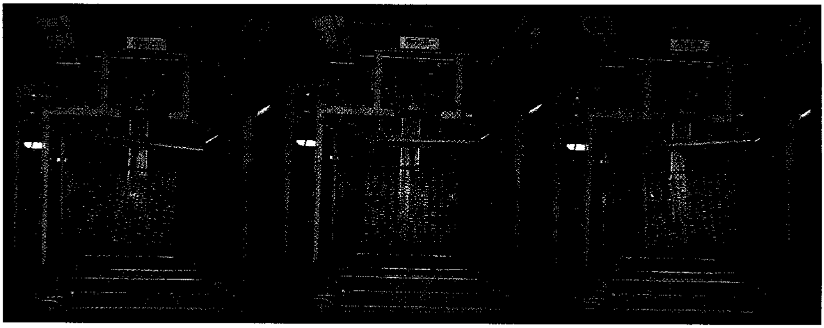

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Abfintech "Absolution" automated hoist systems include many safety features to minimize potential hazards. An operator safety curtain with emergency "bumper" stops, a flexible pendant station for operator convenience, visual and audible safety alerts, and remote control emergency stops are provided for the operator(s) safety and convenience.

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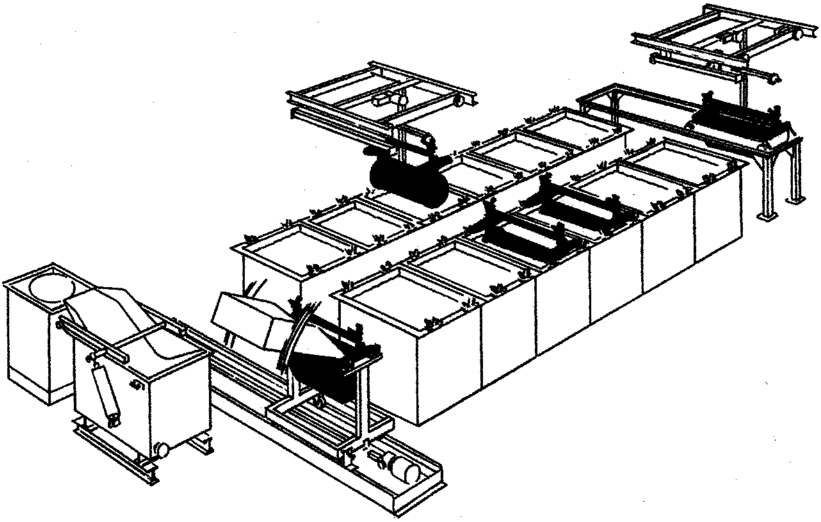


Fig. 1. Oval-shaped programmed-hoist system processing plating barrels.

- Variations in terms of tank layout, size of work, and multiple cycles. Layout of the plating line has virtually no limits and hoist arrangements will conform to straight line, U-shape, and oval-shape systems. Limits are broad regarding the size or weight that a hoist can handle. Some hoists have been built to handle loads like PC boards, others to handle loads up to 6,000 lb. They have also been built to handle 34-ft-long structural aluminum members.
- Compatibility with cell plating where the use of conforming anodes is often desirable or where the work varies considerably from load to load. Each cell can have a different current load and plating time can vary within the broad programming capabilities of the computer hoist controls.
- Simple plating line expansion. Since the transfer carriage and tanks are independent, tanks can easily be added, especially if spaces were provided initially. Adding extra hoists to increase output can also be done with a minimum of cost and downtime.
- At times even an existing plating line can be automated by the addition of the overhead programmed hoists.

In general, the programmed hoist is economical in the range of 5 to 20 barrels or work bars per hour. When the production rate is higher (60–100 racks per hour), the return-type automatic becomes more economical. Figure 1 shows an oval-shaped programmed-hoist system processing barrels.

The program hoist approach to automatic plating and/or processing uses floor- or ceiling-mounted transfer carriages, which advance the work load (barrels, racks, baskets, etc.) from process cell to process cell. The hoist completely releases the work at the cell, thus freeing the hoist to transfer work at other stations, but return at the appointed time to transfer the previously released work to the next station. This type of equipment is particularly desirable where large, bulky pieces or extremely heavy pieces are being plated or processed.

Process controls program the hoist system in accordance with the desired process. The process and cycle may be changed to other preplanned or new cycles.

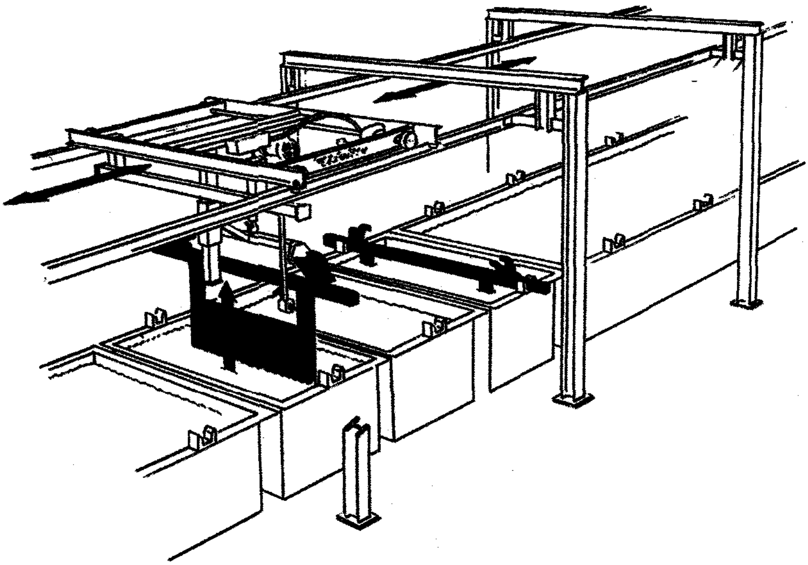


Fig. 2. Straight-line programmed-hoist processing racks.

The Hoist Is Economical

Since the transfer carrier releases the work and uses these interim times to perform other tasks, the hoist does the work of several elevator mechanisms. Loading and unloading areas can be arranged to meet individual plant requirements. The hoist releases the work and does not dwell during loading and unloading. Figure 2 shows a straight-line programmed-hoist processing racks.

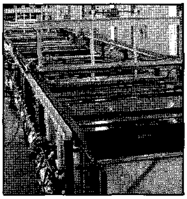
Program Hoist Advantages

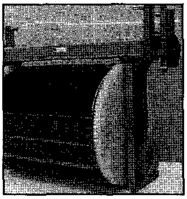
- Multiple machine cycles and plant layout
- Load and unload located for efficient work handling
- Simple, rugged, heavy-duty design and construction
- Adaptability to many plating cycles
- Process control through master control selector
- Permits future expansion and changes
- May automate an existing line
- Reduces manpower requirements
- Ability to handle different parts requiring varying thickness of plate at the same time. This is accomplished through the use of automatic rectifier programming.

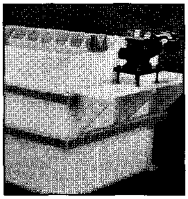
Remember . . . anything that can be done with manual hoists can be accomplished with greater speed, consistency, and economy on a program hoist machine.

THE RETURN-TYPE AUTOMATIC SYSTEM

The return-type automatic can take the form of either an oblique barrel (as shown in Fig. 3) or a rack system (shown later in this article). Major advantages include:







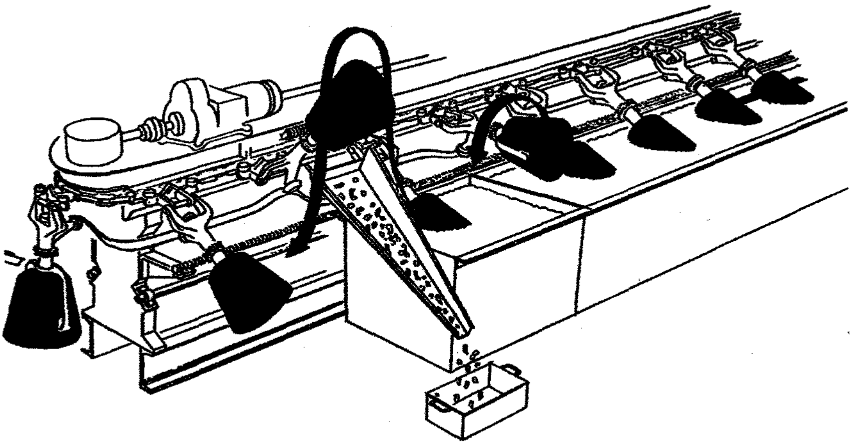


Fig. 3. Return-type automatic processing oblique barrels.

- Greater production capabilities at a lower initial investment than with a hoist. Comparable floor space requirements usually are lower. Production rates as high as 240 racks per hour (with a rack size of 24 in. direction of travel (DOT) × 48 in. deep) are possible on a return-type split-rail rack machine.
- Lower maintenance costs and less downtime due primarily to the lack of sophisticated electric or electronic controls as used on multiple hoist lines.

It should be noted that, of all the different types of machines available today, the split-rail automatic was specifically designed for electroplating. These machines provide for simple, efficient operation. Solutions, electrodes, etc. are easily accessible and the equipment requires little maintenance.

The work carrier supports the work and carries the current. The split-rail rises and descends, elevating and lowering the work carrier. The pusher moves the work carrier through the process cycle with a positive indexing action, which, unlike chain drives, permits variable rack spacing and eliminates problems due to chain stretch and wear.

Rugged, bridge-type integral frame construction supports the entire unit including the tanks. Heavy, permanent, direct buss connections eliminate cable replacement. The largest and heaviest practical rack loads (2,000 lb) can be handled with ease by allowing for the straight vertical lifting of all weight.

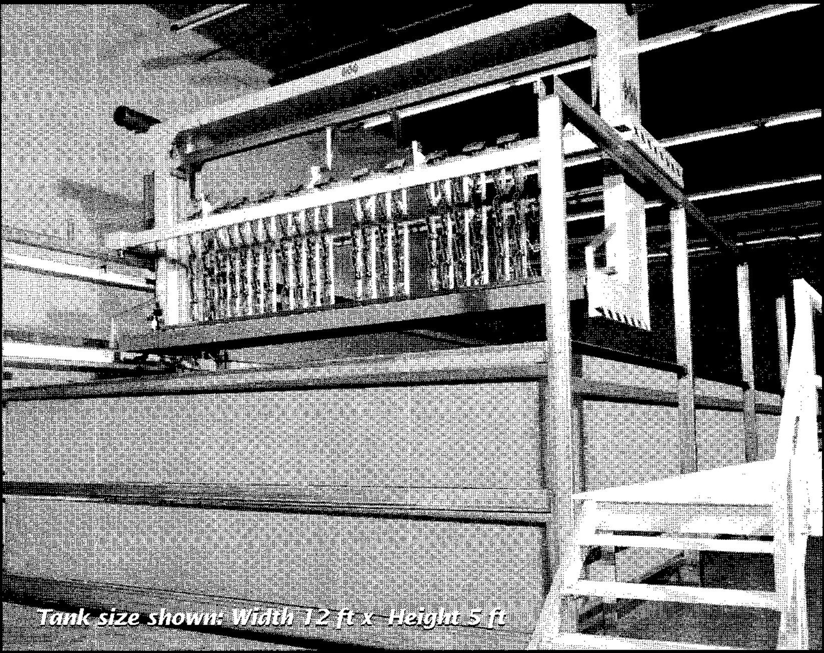
Cushioned hydraulic power plus square transfer eliminates whip, sway, and dropped parts, reducing dragouts and rejects. The smallest number of operating parts minimizes the downtime and maintenance.

The compact design saves plant floor space. Easy accessibility of all components simplifies maintenance. The shortened current path reduces voltage drop and provides larger current capacity per rack with minimum KVA usage and significant energy savings.

Fail-safe control circuit eliminates overtravel. The split-rail principle permits excellent tank ventilation with minimal use of costly exhaust power or make-up air and results in further energy savings.

Split-rail automatics can also have the following special features:

- Delayed dip mechanisms
- Bypass mechanisms



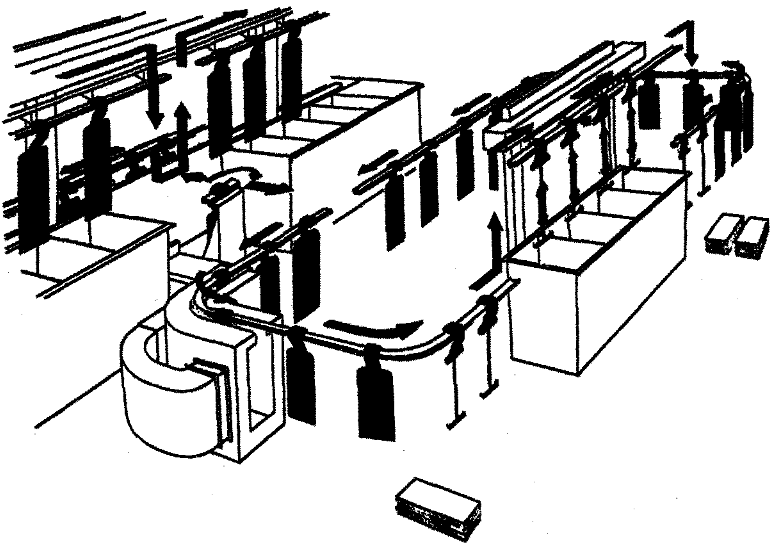


Fig. 4. Plating system with loader, conveyor, dryer, and rack strip.

- Conveyors
- Automatic loaders and unloaders
- End and side nonlift sections

One of the valuable advantages of the pusher-type split-rail full automatic is the simple automatic load and unload. The loader transfers the racks and carriers to the conveyors without manual assistance. The work is dried, unracked, and racked on the conveyor. Such features as rack strip machines may be incorporated in the conveyor system, as shown in Figure 4, and turnstiles may also be installed to turn the racks around so that no personnel or material handling is required inside the conveyor loop.

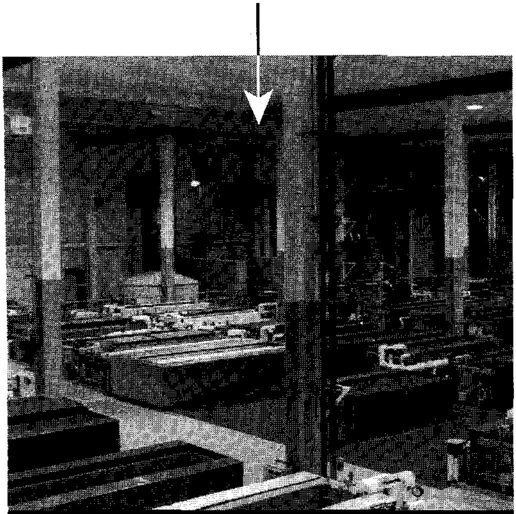
Another flexible feature of the pusher-type split-rail full automatic is its adaptability to the addition of end and side nonlift sections, as shown in Figure 5. These are extensions of the machine for long process periods. A further advantage is that a side nonlift section may be skipped entirely when desired. Also, both types of extensions may be run at different speeds than the machine, to vary the overall process time in the nonlift sections.

Split-Rail Principle

The split-rail principle makes possible many outstanding features:

- Square transfer
- Simple, rugged, high production capacity
- Lowest KVA per ampere plated
- Excellent tank ventilation with minimum air usage
- Virtually unlimited rack capacities
- Minimum floor space requirements

Simple pusher mechanism allows for:



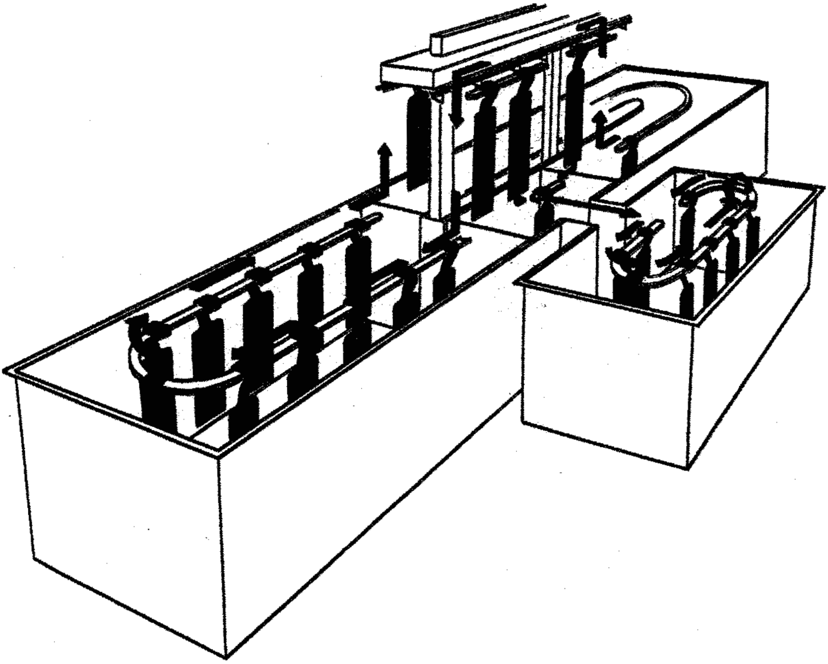


Fig. 5. Split-rail machine with end and side nonlift sections.

- Variable rack spacing for optimum plating results.
- Precise rack position after each index.
- Simplicity of change in rack spacing.

Sequence of Operations

Basic machine cycle may be broken down into five motions or time phases. They are dwell, down index, up travel, up index, and down transfer.

The cycle time equals 1 + 2 + 3 + 4 + 5. Transfer time is the time required from the time a rack starts being raised from one tank until it is completely immersed in the next tank and equals 3 + 4 + 5. (See Fig. 6.) The illustration shows the motion of a rack through a complete time cycle of the machine and the position of these racks at the end of each motion or time phase.

Hydraulic Drive and Motion Control

The low-pressure hydraulic units provide the following advantages:

- Independent control of each motion.
- Control of lift speed reduces dragout by "wiping" rack free of solution as it exits the tank.
- Control of descent speed prevents dishing, swimming, or loss of parts.
- Control of transfer speed with cushion prevents whip and sway, which cause loss of parts.
- Every movement of the machine can be adjusted to suit the characteristics of the part being processed.

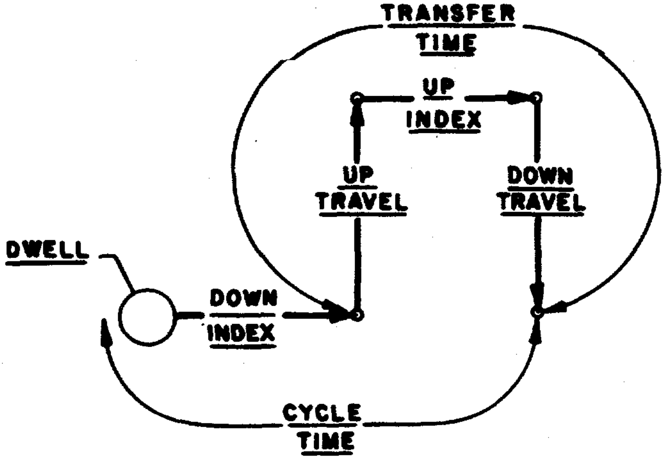


Fig. 6. Sequence of operations.

COMPARISON—RETURN AUTOMATIC VS. HOIST

Table I provides a cost comparison between a high-production split-rail return-type automatic and programmed-hoist system; both processing a rack size of 18 in. DOT × 14 in. × 48 in. deep.

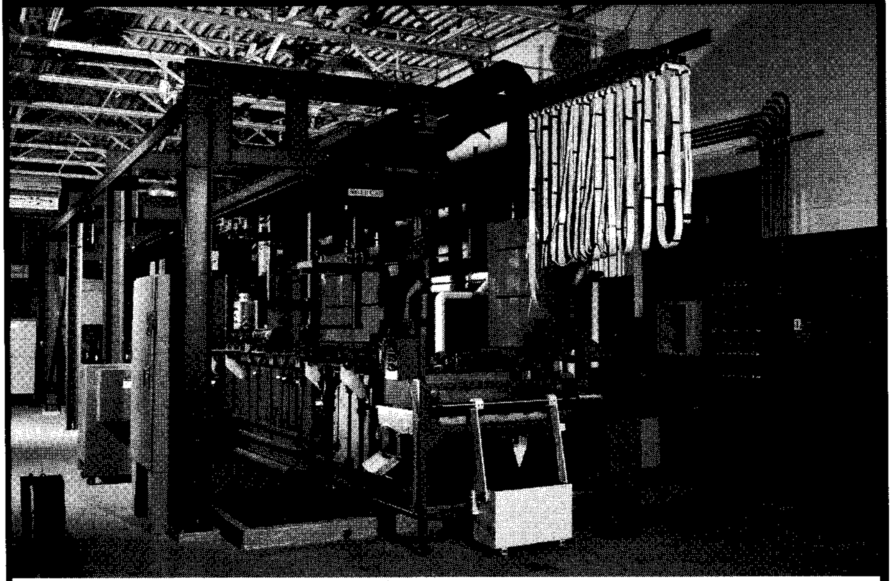
As you can see in Table I, the programmed-hoist system would initially cost more, plus operating costs years down the line would be much greater; therefore, in selecting automatic plating equipment, one must consider production requirements (high/low), material flow and handling, available floor space, process cycle, base metal (steel, die cast, brass, aluminum, etc.), and annual operating costs.

SIDE-ARM MACHINE

Another return-type automatic is a side-arm machine as shown in Figure 7. The side-arm automatic is a mechanically driven, chain-type machine with hydraulic power on the lift and

Table I. Cost Comparison

	Return-Type Automatic (Single Row) (100 Racks/Hour)	*Programmed-Hoist System (6 Racks/Carrier) (16.7 Carriers/Hour)*
Basic machine complete with controls, carriers, and process tanks	—	—
Solution heaters and temperature control	—	+10%
Air-agitation equipment	—	+15%
Cooling equipment	—	—
Solution filtration	—	—
Exhaust ventilation and make-up air	—	+50%
DC power supply	—	+5%
Field installation	—	+20%
Floor space requirements	—	+30%
Annual operating costs of BTU, KVA, CFM & labor	—	+??



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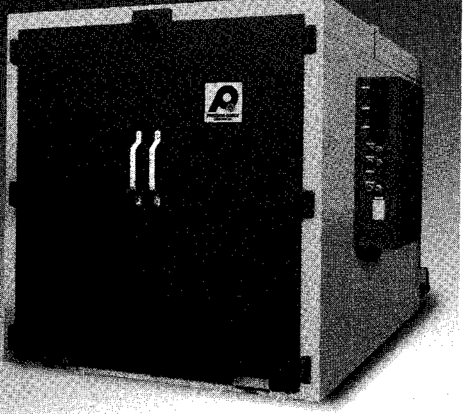

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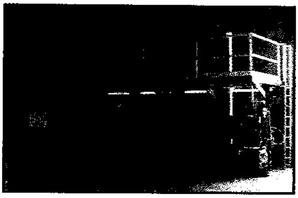

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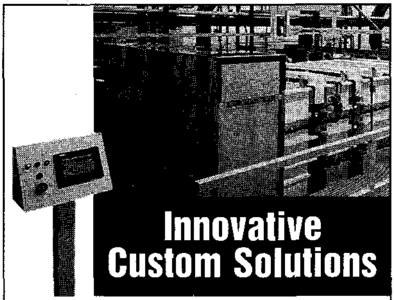

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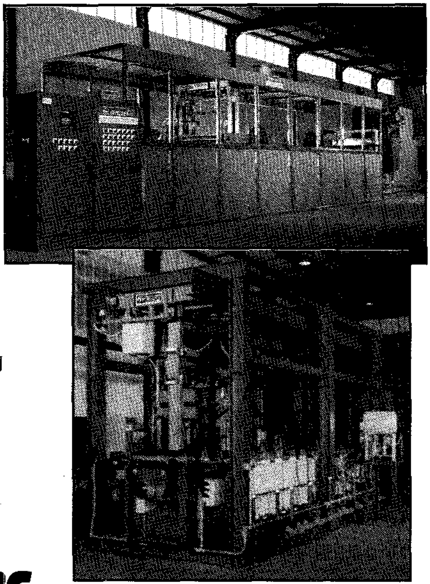

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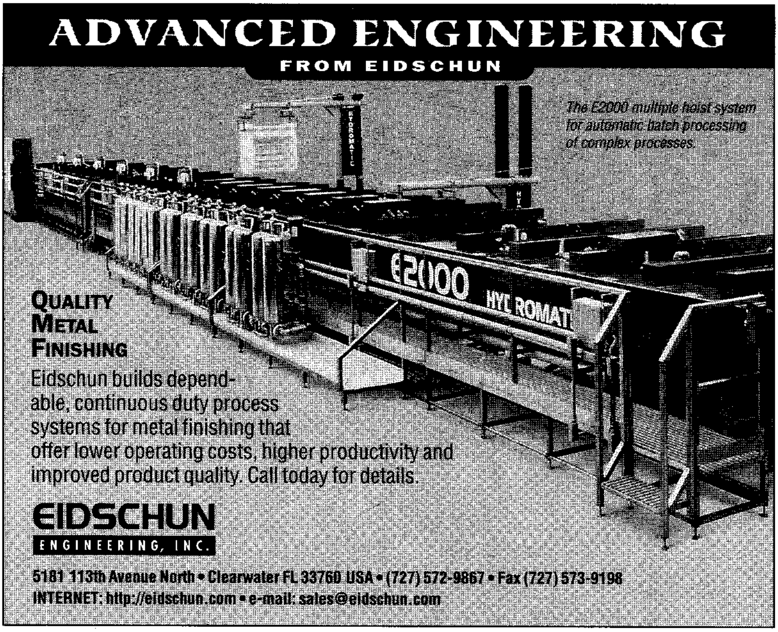

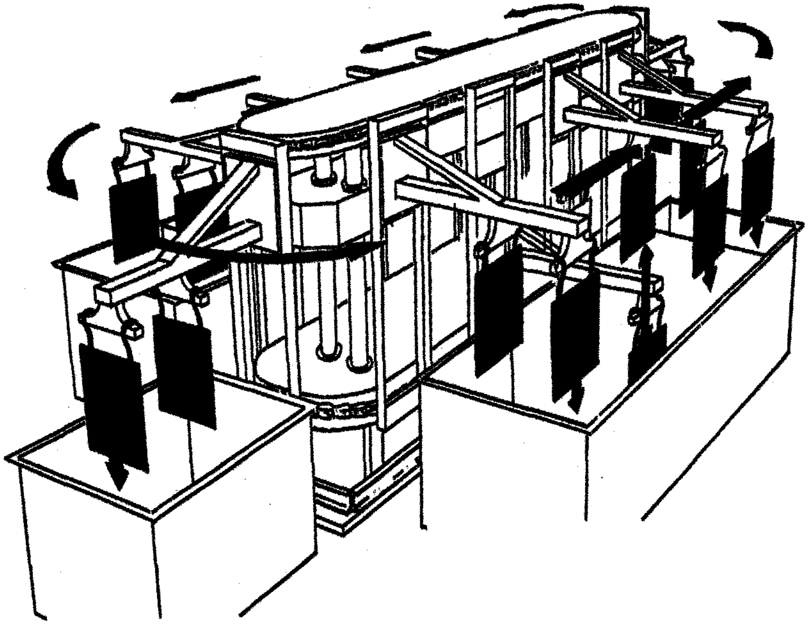

Fig. 7. Side-arm machine

transfer drives. Generally it is used as a double-row unit for large racks with a working capacity of up to 120 arm loads per hour. This machine is particularly popular for multiple skip cycles, such as anodizing or preplate on plastic, and also can be supplied with up-arm storage.

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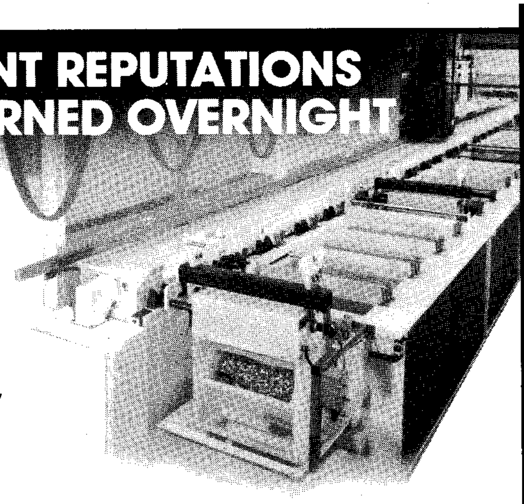
ADDITIONAL EQUIPMENT

To complement basic hoist and conveyor systems, manufacturers have many auxiliary items to custom-automate plating layouts. Rack loaders and unloaders, oscillation assemblies, and automatic cycle selectors are among the stock devices that can be included.

Specialty machines also are available and are usually custom designed for a particular part or process. Initially, of course, they cost more. A specific example is a finger machine designed to hard chrome plate the stems of automotive valves. The solution level is controlled automatically to cover only the stems. The valves are loaded and unloaded automatically.

While such machines are apparently unique, a slight redesign may help adapt them to other plating situations. As with the basic hoists and conveyors, specialty equipment requirements are more accurately determined and analyzed after discussions with a variety of equipment manufacturers.



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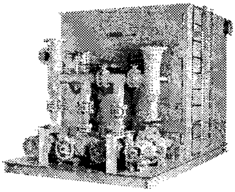

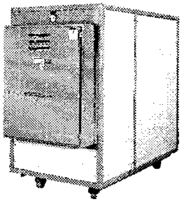

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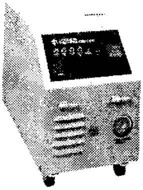

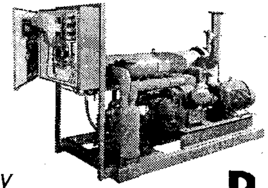

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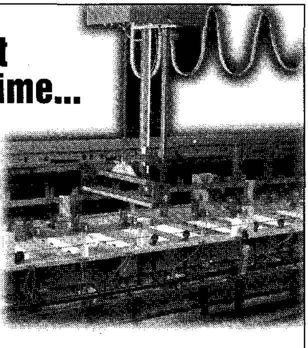
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CONTINUOUS STRIP PLATING OF ELECTRONIC COMPONENTS

by John G. Donaldson

Consultant, Tustin, Calif.

Stamped and preformed electrical contacts attached to a carrying strip, machined or "loose-piece" contacts held by a narrow metal band (bandolier), and solid strip are typical of the materials plated in continuous lengths in specially designed equipment using chemical processes developed for high-speed performance. The entire surface of the strip or parts being processed may be plated, or the deposits may be restricted to small discrete areas using one of several types of selective plating techniques.

Two divisions of the electronics industry, connectors and semiconductors, utilize most of the products produced by strip plating; predominately, connector contacts, lead frames, various connecting devices, leads, headers, or the solid strip materials from which contacts and components are subsequently formed. Gold, silver, or tin and tin-lead alloys are the deposits most often specified, usually over barrier coatings of nickel or copper. Other metals also being specified as a coating on electronic devices include palladium, palladium-nickel, tin-nickel, and cadmium.

Copper and its alloys, particularly phosphor bronze, brass, beryllium copper, nickel, and nickel-iron alloys (i.e., Kovar and 52 alloy), nickel silver, steel, and stainless steel are the base metals usually plated. The thickness of these materials will typically be between 0.005 and 0.020 in., although requirements for as low as 0.002 in. or as high as 0.040 in. are not unusual. Strip widths, including the carrier, generally run between approximately 0.5 in. and 3.0 in., but both wider and narrower materials are being processed for particular applications.

EQUIPMENT

From a strictly mechanical viewpoint, the principle of reel-to-reel plating is deceptively simple. Unreel the unplated material from a feed coil, convey it through a series of processing stations, and re-coil the finished product onto a take-up reel. Due to the shapes, sizes, and fragility of the materials being plated, however, and because of the number of difficult and complex plating requirements specified, continuous reel-to-reel plating is a relatively complex and difficult operation. So much so, in fact, that the equipment must usually be customized to at least some degree for each application.

Most strip plating lines are comprised of six main sections:

1. De-reeling.
2. Preplating—including cleaning, etching, and activation.
3. Plating either overall or selective.
4. A postplating section for (a) precious metal recovery, (b) special postplating treatments, if required, and (c) drying.
5. Reeling.
6. Drive, transporting, and contacting system.

How each of these is constructed depends on the type and configuration of materials to be processed and the plating requirements. The ability for one line to process a large variety of shapes, sizes, and types of materials is a hoped-for feature of any continuous plating equipment; however, the trade-off between a practical machine and a very complex one, which is difficult to impossible to operate and maintain, must be recognized when the equipment is being designed.

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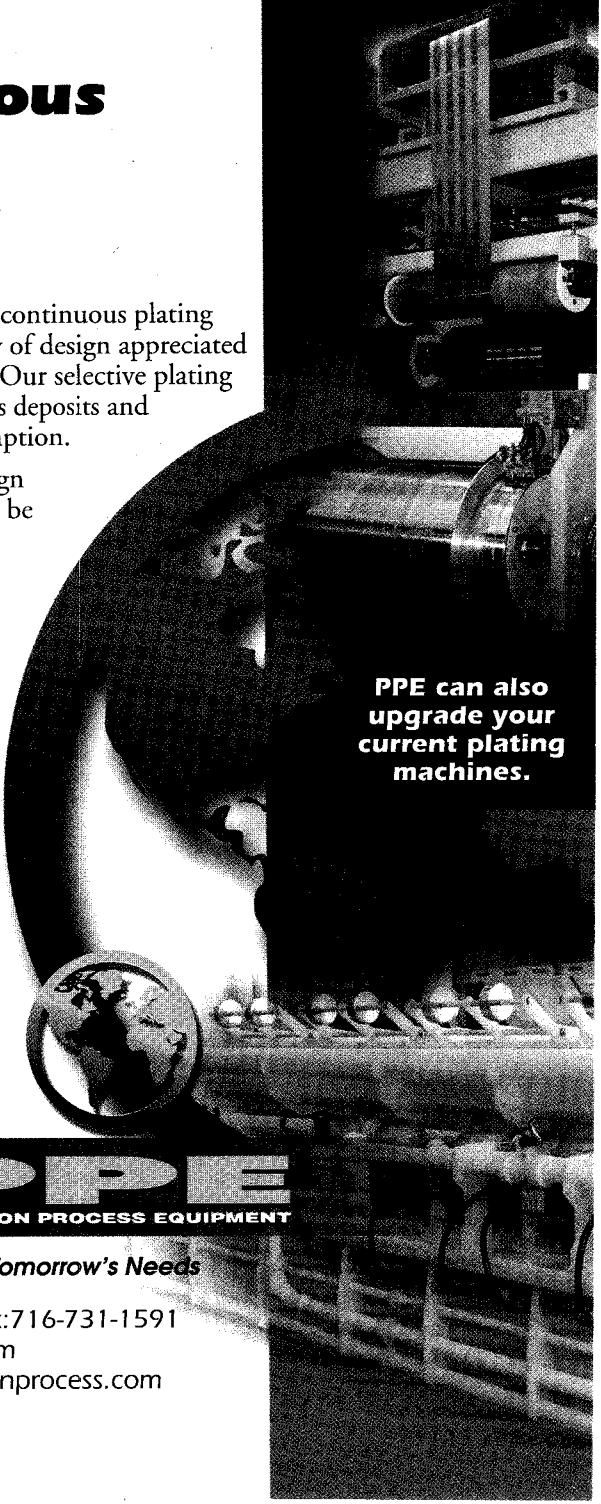

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Continuous strip plating is performed with the strip materials conveyed through the equipment horizontally or vertically. In the latter case, conveying and handling the strip is more complicated but this technique is usually preferred because:

1. Cleaning, rinsing, and activation processes are improved.
2. Plating thickness will be much more uniform per side and also side to side.
3. Higher solution agitation rates are possible.
4. Drag-out is reduced.
5. Anodes can be more strategically placed, adjusted, and maintained.
6. Selective plating can be done by controlled depth immersion.

The general design of a processing station is comprised of two sections, an upper process cell and a lower reservoir tank. The solution is pumped from the reservoir into the upper cell where, when reaching the desired level, it flows over weirs or downspouts back to the reservoir. Heating and filtering of the solutions are generally performed in the reservoir.

As the material being plated leaves each process cell, air knives and/or soft rubber wipers are required to remove drag-out. Spray rinses follow each operation, with air and mechanical wipers again employed to prevent diluting the subsequent solutions. (An important point to remember is that the materials being plated, due to their configurations and the speed at which they are run, will carry a considerable amount of solution with them as they exit each station. Rapid depletion of the solutions, or contamination of those next in line, must be avoided.)

At each processing station, where the strip must be made cathodic or anodic, one or more of several types of contacting is used. Examples of these are:

1. Through the stainless steel drive or guide sprockets.
2. Copper alloy contact rolls.
3. Copper or nickel wiping strips.
4. Soft stainless steel or copper alloy brushes.

The type and design of the contacts used are important and depend on the style of parts being plated. A firm contact force is necessary to prevent interruption of current, but it must not be so firm that the materials are mechanically damaged.

Contact rolls and brushes must be kept clean and smooth to avoid arcing and burning. (Sometimes they are nickel and gold plated to improve their function.) It is necessary to position the contacts as closely as possible to the process cell to prevent overheating and drying, or oxidizing the materials being plated; however, not so close that they might be contaminated by the solutions. When possible, contacting is performed in the rinse stations where the water helps keep the contacts clean and cool.

SELECTIVE PLATING SYSTEMS

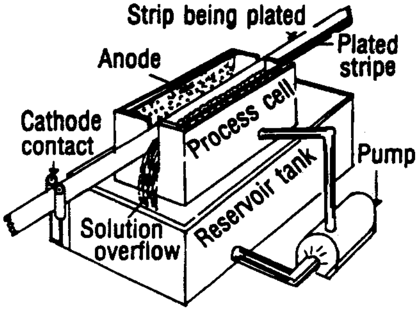
The selective plating of strip materials for electronics applications is an important process capability for both economic and technical reasons. Being able to deposit a precious metal only where it's actually required for its functional attributes will obviously result in an electrical component that will be far less costly than if it had been plated overall. Of almost equal importance to the electronics engineer is the need to preclude plating from certain zones, or to utilize the characteristics of two, or even three, types of plating on a single contact—something made possible by selective plating.

There are a number of selective plating techniques employed, each with its advantages, but none without at least a few operational and/or maintenance problems.

Controlled Depth or Tip Plating

The simplest method of selective plating is to only partially immerse the material being plated into the plating solution (Fig. 1). The height of the deposit is set with adjustable

Fig. 1. Controlled depth plating cell. Notes: (1) Heating and filtering are usually performed in the reservoir tank. (2) Level of solution in process cell controlled by weirs at slots or by downspouts. (3) Cells of the same design are used for cleaning and activation and solutions maintained so that the strip is entirely submerged.



solution overflow weirs and/or downspouts and by the position of the guide sprockets. Plastic or glass shields can be used to improve plating thickness uniformity; however, it is impossible to avoid plating the entire submerged surface and this is the main drawback of the technique.

Another unavoidable problem is the "loss" of some precious metals because of the meniscus at the surface of the solution. This zone will range in width from approximately 0.045 to 0.065 in. and over a period of time a significant amount of precious metal (i.e., gold) will be plated in that area.

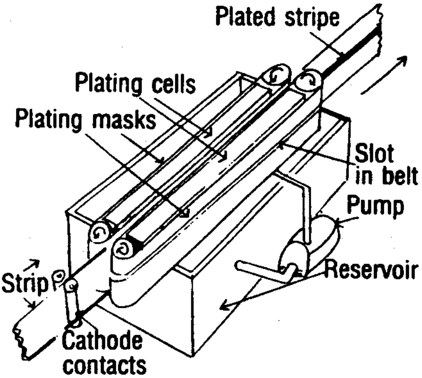
Moving Belts

Belts made of soft rubber bonded to an insoluble metal backing strip prevent the plating solutions from reaching the surface except for narrow bands or spots on the materials being plated (Fig. 2). The plating solution is jetted from a plating cell through slots or holes in the masking belts firmly pressed against and turning with the strip. Solid materials and preformed components can be plated with one or more stripes on one or both sides. If properly designed and built, the moving belt can be expected to hold a stripe width tolerance of at least ±0.010 in.

Two individual belts can also be used to produce a stripe, with stripe location and width adjusted with guiding pulleys. With this system, stripe width cannot be as closely controlled.

The somewhat higher cost of equipment and the fact that specially fabricated belts are required for each family of parts being plated are the two most often-voiced objections to the moving belt selective plating system.

Fig. 2. Moving belt mask. Plating solution touches the strip only in the slotted area. Stripes may be on one or both sides; spots can also be plated via this technique.



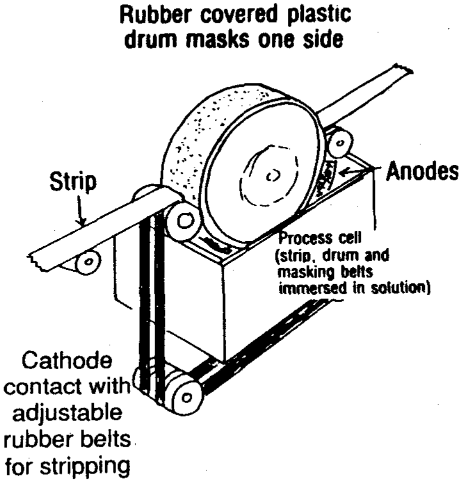


Fig. 3. Drum and mask selective plating.

Belt and Drum

A rubber covered drum masks the back of the strip being plated and two rubber belts are used to produce the selectively plated stripe as shown in Fig. 3. The width and location of the stripe are controlled by the placement of the belts.

This system may also be used for tip plating by allowing the material to protrude laterally from between the drum and a masking belt.

Belt and drum selective plating compares technically with the moving belt system; however, it may lack some of its versatility and precision. Also, when used for spot plating, it is very difficult to precisely synchronize belt, drum, and strip speed.

Tape Masking

This is a novel technique, pictured in Figure 4, in which a thin Mylar tape is "tooled" by prepunching where plating is required. The tape is then compressed against the strip, which must be solid, as it passes over the plating cell.

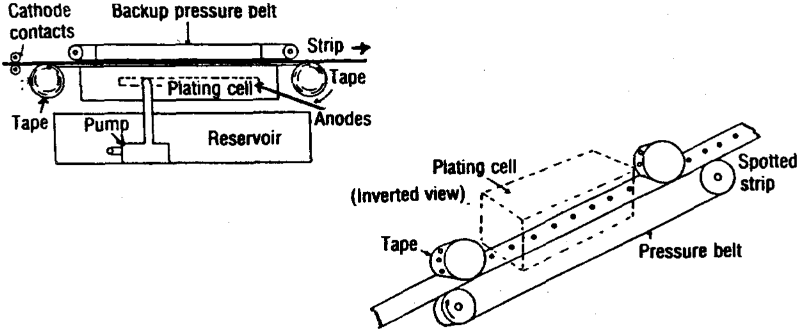


Fig. 4. Tape masking. Thin Mylar (or equivalent material) is prepunched with slots or holes. It is then held firmly against the strip being plated as it passes over the plating cell.

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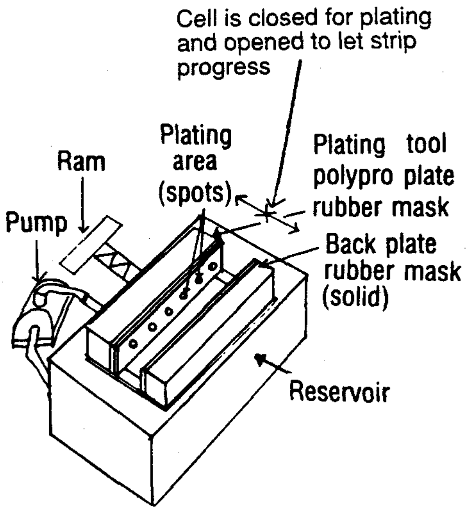

Fig. 5. Spot plating cell. Step-and-repeat system is hydraulic, clamshell, or air driven.

Strip widths as narrow as approximately 0.010 in. and spots 0.020 in. in diameter can be produced with tolerances of approximately ±0.005 in. The process is not widely used because it doesn't lend itself to large scale production and is applicable only to solid strip.

Spot Plating (Step and Repeat)

Small, well-defined, round or rectangular plated spots are produced by spot plating using rubber masks backed by a rigid plastic as depicted in Figure 5. The technique is used primarily for plating the tips of semiconductor lead frames and can also be employed for plating tiny discrete spots on strip materials before they are formed into contacts or components. Using specially designed, form-fitting plating cells, the procedure could be employed to spot plate preformed components and contacts.

To obtain the spots in precise locations, prepunched guideholes are used to position the strip. In most spot plating equipment, the strip is intermittently advanced through the plating cells by a step-and-repeat system. The plating masks or plating tools, precision-molded silicon rubber, are closed on the strip via a clamshell mechanism during the plating cycle. Typically, from about five to 20 spots are plated at the same time.

Step-and-repeat selective plating permits the very precise location of well-defined and discrete plated spots. The main disadvantages are lowered production rates and the requirement for particular masks for each application.

Brush Plating

An absorbent pad, such as one made of felt, is used to conduct plating solution to only that area of the strip where plating is required. The pad, which may be in the form of a roller or a narrow belt, shown respectively in Figs. 6 and 7, is backed by an insoluble metal anode. The pad is saturated as it turns through the plating solution when the roller technique is used, or by wicking in the case of the belt arrangement.

Brush plating is an excellent method for limiting the plating to the raised contacting surfaces of electrical contacts and can be employed to plate only one or two sides of

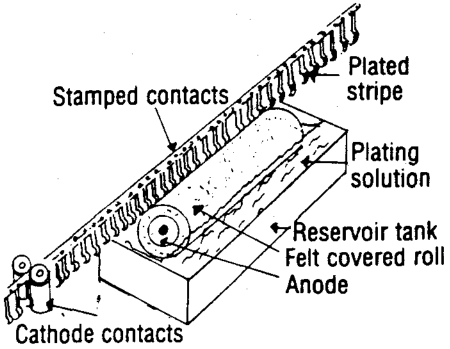

Fig. 6. Selective brush plating. (U.S. Patents 4,064,019 and 4,078,982)

rectangularly shaped connector pins. It is also very effective for tab plating printed circuits and can be used for such applications as plating the contacting pads of membrane-type electrical switches.

Other Methods

Several other ways for selectively plating continuous strip materials have been developed, but are not in general use. These include:

- Slotted wheels with the solution jetted through the slots (or holes) in the wheel.
- Using continuously applied photoresists, inks, or paints.
- Controlled jet plating with the electrolyte directed in a small steam at the area to be plated.
- Using specially shaped and shielded anodes placed very close to the workpiece in the area where plating is desired.

Although these techniques are effective, for reasons both economic and technical, they are seldom used when high volumes of components are being produced.

HIGH-SPEED PROCESSES

To produce the great numbers of components required by the electronics industry, it is necessary to operate the equipment at speeds of at least 10 to 50 or more feet per minute (fpm). Thus, a fraction of the time normally desired for preplating and plating operations is

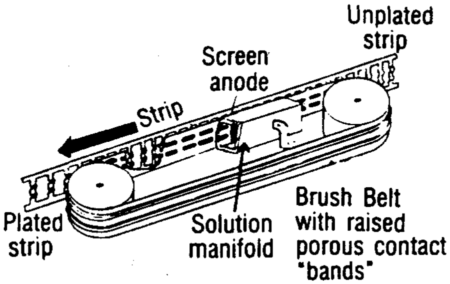

Fig. 7. Brush belt plater.

allowed. For example, when running at 25 fpm, the material remains in a 5-ft processing cell only 12 seconds, allowing little time for cleaning, activation, etching, or plating.

Because each component, or each millimeter of strip being plated, is subjected to exactly the same conditions in a processing cell as all others, the extended treatment times required for bulk plating are not necessary. Nevertheless, the very short immersion times possible made it mandatory that, along with the development of continuous strip plating equipment, the effectiveness of the solutions had to be improved, either through adaptations in chemistry, changes in operating conditions, or by employing such assists as ultrasonics and pulsed current.

Some of the mechanics used to improve solution effectiveness are:

1. High solution flow rate.
2. Direct solution impingement.
3. High-velocity spray.
4. Increased solution temperature.
5. Increased chemical concentrations.
6. Close anode placement.
7. High solution agitation (stirring, ultrasonics, vibrators).

HIGH-SPEED PLATING

High-speed plating is the term used to describe solutions with greater than traditional deposition rates because of increased solution efficiency and higher limiting current densities. Most plating process supply firms market high-speed plating solutions tailored to meet the needs of the continuous strip plater. Metal concentrations and solution conductivity are higher than with conventional solutions and higher than normal operating temperatures and solution agitation rates are specified.

Because the plating on electrical components imparts critical functional characteristics, much care must be taken to assure that the higher speed processes produce a satisfactory deposit. Such features as hardness, wearability, bondability, and solderability are all significantly affected by the structure of the deposit, the presence of impurities, and by minute differences in the percentages of hardening elements.

Obviously, it is important that the solution operating parameters be constantly monitored and closely controlled. Good filtration is necessary and continuous carbon treatment of all plating solutions is advisable. The plating and processing cells as well as the reservoir tanks should be covered to avoid airborne and accidental contamination.

METAL PREPARATION

The processes used for pretreating materials being reel-to-reel plated are basically the same as those employed in other types of plating operations; however, since immersion times are very short, varying from approximately 15 to 30 seconds, some modification in make-up may be required and good solution maintenance is critical.

To meet the high-quality standards required in components used in electronic devices, excellent and reliable surface preparation is essential. This means that both the processing cells and the preplating solutions must be designed to ensure the complete removal of soils and oxides or surface films. Further, the systems must be so engineered that recontamination of the surfaces is impossible. For example, the air used for wiping must be dry and filtered and the materials being plated must not be allowed to dry between any of the operations being performed.

The surfaces of most materials being reel-to-reel plated will be contaminated with both organic and inorganic soils. Light duty cutting and rolling oils, plus airborne shop oils are the source of the organics. The inorganic materials exist in the form of light oxides and heat scales, dust and dirt particles, and, occasionally, surfaces lightly corroded due to poor handling and storage.

Small surface scratches from the rolling and forming operations are not uncommon and burrs produced during stamping and cutting are usually present to some degree. When the plating is to be nonporous and/or the burrs need to be removed, a polishing (i.e., electropolishing) step must be included in the pretreatment sequence.

When the types of materials to be processed are limited to but a very few, and the type and extent of the soils that must be removed are known, the preplating cycle can be relatively simple. It may consist of only a few operations:

1. Alkaline soak clean.
2. Rinse.
3. Alkaline electroclean.
4. Rinse.
5. Acid activation (deoxidize).
6. Rinse.
7. Plate.

Both job shop and captive plating departments may anticipate that the basis material to be plated, its surface condition, and the surface contaminants will vary considerably, so it is necessary to engineer a more flexible pretreatment section, one capable of handling at least most of the conditions that might be encountered. For this, the following sequence might be designed:

1. Vapor or spray degreasing.
2. Alkaline soak.
3. Rinse.
4. Electroclean (cathodic or anodic).
5. Rinse.
6. Electroclean (cathodic or anodic).
7. Rinse.
8. Electropolish (i.e., 50% phosphoric acid).
9. Hot rinse.
10. Acid activation (i.e., 10% sulfuric acid or 25% fluoboric acid).
11. Rinse.
12. Strike or plate.

In some processes, additional tools may be required to assist in removing particularly heavy soils and oxides. These include chemical etches, mechanical brushing, and periodic reverse or pulsed electrocleaning.

Plating Cycles Recommended for Specific Metals (Rinses Not Indicated)

Phos Bronze/Beryllium Copper

1. Degrease.
2. Alkaline electroclean (anodic).
3. Electropolish—optional (50% phosphoric acid).
4. Acid activate (40% fluoboric acid or 20% sulfuric acid).
5. Strike (avoid immersion plating).
6. Plate.

Nickel/Nickel Alloy

1. Degrease (may not be required).
2. Alkaline electroclean (anodic).
3. Electropolish.
4. Activation (20% fluoboric acid cathodic, or proprietary activators).
5. Strike (low metal, high conductivity, high current density).
6. Plate.

Ferrous Nickel Alloys (i.e., 52 NiFe, Kovar)

Same cycle as for nickel except activation may be accomplished in 50% hydrochloric acid.

Stainless Steels

1. Degrease.
2. Alkaline electroclean (cathodic).
3. Activation (50% hydrochloric acid, 6 V cathodic).
   or
3. Activation (Woods nickel strike—anodic 4–6 V).
4. Woods nickel strike (40–50 A/ft^2).
5. Strike.
6. Plate.

A typical process sequence for nickel, gold stripe, and solder plating is shown in Figure 8.

PLATING SOLUTIONS

As indicated earlier, the solutions used for reel-to-reel plating usually contain the same constituents as those used for other types of plating. To convert them to high-speed processes,

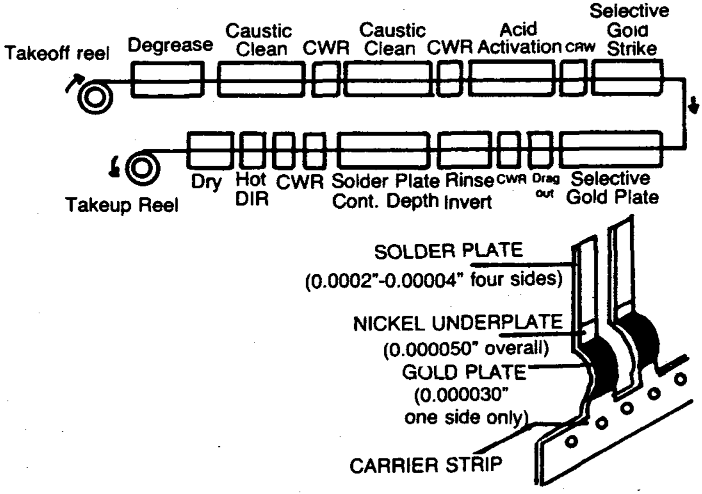

Fig. 8. Typical process for nickel plating, gold striping, and solder plating a stamped connector contact.

the metal concentration and that of some of the other constituents are increased and such operating conditions as temperature and pH are modified to produce improved deposits at higher current densities.

Proprietary high-speed solutions tailored for reel-to-reel plating are available from a number of plating process supply companies. The properties of the deposits have been engineered to meet the critical requirements of the electronics industry and the operation of the solutions is kept fairly simple to enable good control.

Solution formulas found elsewhere in this *Guidebook* can serve as the basis for solutions to be used for reel-to-reel plating. High efficiency solutions for copper, nickel sulfamate, and silver are described that can be run with the concentrations shown. For the standard formulas, however, increasing the metal content from 25 to 50%, possibly with similar increases in the main conducting salts, may be necessary to reach the current densities required for optimum production rates. Adjustments to the pH and operating at higher than specified temperatures also may be required.

TANK DIMENSIONS

The width and depth of the processing tanks for a reel-to-reel plating line depend on the size, shape, and number of strips to be plated. When anodes are required, or cathodes in the case of anodic current, they should be positioned as close to the strip(s) as possible, but not so close that shorting can occur. A space of 2–4 in. is generally used.

The length of the tanks is decided by determining the operating rates needed and knowing how long the immersion time must be for each process. The latter can sometimes be established by a series of laboratory-style experiments and required operating speeds calculated from total production requirements. Once these factors have been found, the length of the processing tank is calculated by the simple formula:

Rate (ft/min.) × immersion time (min.) = tank length (ft)

A complete exercise to determine length might go, in part, like this:

Required: 3 million of contact X per month
2 million of contact Y per month
1 million of contact Z per month

Contacts/ft: X = 30; Y = 40; Z = 50
No. of feet req'd: X = 100,000; Y = 50,000; Z = 20,000
Total per month = 170,000 ft
One shift operation, average 20 days per month
170,000/20 = 8,500 ft/day
8,500/7 hr = 1,215 ft/hr
= 20.25 ft/min (25 to be safe)

Immersion (dwell) time for Process A = 10 seconds
B = 15 seconds

Process A Tank: 25 ft/min. × 0.167 min. = 4.175 ft
Process B Tank: 25 ft/min. × 0.25 min. = 6.25 ft

The type of basis metal being plated, the condition of its surface, the size and design of the parts, and the type and amount of plating specified all have a direct effect on the time required to successfully pretreat and plate strip and preformed components. It is not possible to predict exactly how much time will be required for each step, but experience has shown that there are ranges of time that can be expected for most applications.

Table I lists the approximate immersion or dwell times required for the various processes named. Experience has shown that most cleaners are usually able to do their job in 12 to 24 seconds on most materials. Electropolishing may require 5 to 15 seconds and acid activators

Table I. Typical Dwell Times

Process	*Type*	*Time (seconds)*
Degreasing	Solvent spray	10–15
Cleaning	Alkaline soak	15–30
Cleaning	Electrolytic	12–20
Electropolishing	Electrolytic	5–15
Activation	Acids, strikes	4–12
Rinsing[a]	High-velocity sprays	3–5
Drying	Blown hot air	15–45 (incl. cool down)

[a] Adequate rinsing can be accomplished in approximately 3–5 seconds with well-directed, high-velocity sprays. The importance of good rinsing and the short time usually allowed for this operation in continuous plating equipment dictates that the rinsing stations be inspected at regular intervals to assure that all nozzles are functioning.

4 to 12 seconds. Plating times vary with the metals being plated, the deposition rates of each type of solution, and the current densities to be used.

Current density, solution efficiency, deposition rate (at the current density used and in the type of plating cell employed), and the required thickness are the factors used to calculate dwell times required for each type of plating solution. When proprietary solutions are purchased, the vendors usually can provide data for each of their plating solutions that enable fairly reliable estimates of the plating times required.

When these data are not available, information in this *Guidebook* and other texts can be used to estimate how long a plating station will be required to obtain deposits of a specified thickness.

As an example, the length of a tank required to obtain a nickel deposit of 0.000050 in. would be about seven feet if a production rate of 25 ft/min is planned and a current density of 200 A/ft^2 is assumed (see *Note* that follows).

Given: A-hr to deposit 0.0001 in. nickel = 1.9 (100% eff.)
1. 1.9/2 = 0.95 A-hr for 0.000050 in.
2. 0.95 A-hr/200 A = 0.00475 hr at 200 A/ft^2.
3. Rate (ft/min.) × immersion time (min.) tank length
25 0ft/min.) × [60 × 0.00475] (min.) = 7.125 ft.

Note: When estimating the maximum current density that will be used, an important factor that must be considered is how much current can be carried by the strip, and in particular, the carrying strip, or bandolier, both between the contact to strip location and between the carrying strip and the contacts being plated. The small cross-sectional area limits the amount of current that can be conducted without causing excessive heating, thereby drying the strip out between stations, oxidizing the surface, or actually melting it. Because of this, the maximum high current densities allowed by high-speed solutions sometimes cannot be employed.

When possible, it is advisable to perform conductivity tests on the actual materials to be plated. A very simple technique is to use a given length of the strip to conduct DC current. Increase the current gradually until water, applied by a spray bottle, dries too rapidly, indicating that in production the strip should not be expected to successfully carry more than that current.

PROCESS CONTROL

The importance of good process control in continuous reel-to-reel plating cannot be overemphasized. First, there is the fact that but a few seconds are allowed in each solution, rather than several minutes as in barrel or rack lines. Second, electrodeposits on electrical components are there to provide function, reliability, and long life; hence, the quality must be consistently good on every inch and on every part in every reel. Third, there is the aspect of cost. High costs can be incurred as a result of subsequent manufacturing and assembly problems due to intermittent and undetectable plating defects within the plated reels, and can also result from excessive use of gold or other precious metals because of processing irregularities.

The frequency of solution analysis, which should include the preplating as well as plating baths, should be established on the basis of operating time, factoring in such items as the types of materials being plated (i.e., plating specifications, drag-out capacity, A-hr consumed, and machine speeds). Process control charts maintained at each station signal trends and help avoid out-of- spec operation.

Note: In designing the processing tanks, the reservoir cell should be constructed to hold as much solution as practical to help control fluctuations in concentrations and suppress the effects of contaminants. The design of the reservoir should also be such that additions of chemicals can be easily made. Water can be added automatically to maintain the required volumes.

There are sophisticated techniques available for continuously analyzing plating solutions. Further, it is possible that these analyses may be used to direct automatic additions of chemicals to the baths. Obviously, the equipment required for these functions will significantly increase the cost of a plating line; however, this increase could be quickly justified by the prevention of a few major quality problems and/or enabling closer gold plating thickness control.

Process control in continuous plating encompasses equipment as well as solution maintenance. Spray rinses need to be checked frequently. The air knives, or air wipes, have to be looked at regularly, as well as any mechanical devices used to avoid or reduce drag-out. In the processing cells, anodes and solution levels need to be looked at frequently as do the electrical contacts, and all of the ancillary and supporting equipment must be inspected and maintained.

OTHER CONSIDERATIONS

DC Current and Rectification

Although high current densities are used in continuous strip plating, the total number of amperes required is rather low because of the small surface area present in each plating station. Therefore, in choosing a power source, there are three main features that should be included:

1. Ripple, which for precious metals is recommended to be held to $<1\%$.
2. Precise current control for the entire range of current supplied.
3. The ability to maintain a constant current density.

Contacts

The contacts used to supply current to the strip must be designed to be effective and reliable and to require little attention because even very brief periods of intermittent contact will result in the production of many feet of defective material.

Parts Counters

Parts counters should not be considered an expendable option. One is needed on both ends of the line to preclude arguments with the base material supplier and the receiver of the plated parts.

Liquid Level Controllers

Liquid levels should be automatically maintained in the reservoir tanks to assure that operating variables are kept within the required control limits.

Tank Heaters

Quartz, Teflon, stainless steel, and tungsten heating elements are most often used. Low level safety switches must be included to avoid the possibility of fires.

INSPECTION

As in any plating for electronics operation, the finished product will be subjected to a number of tests to assure good plating quality. Typically these tests will include:

1. Adherence: twist, bend, bake, and/or tape.
2. Appearance: visual and microscopic to 20×.
3. Bondability: a use test for lead frames.
4. Porosity: nitric acid vapors or immersion, electrolytic, gas.
5. Solderability.
6. Thickness: X-ray, beta backscatter, microsection.

Continuous thickness testing equipment is available, which can be used to control the thickness of the deposits as well as to monitor them. Experience has show that the seemingly high cost of such a capability is soon recouped through conservation of precious metals.

ACID-RESISTANT FLOOR CONSTRUCTION

by Donald J. Kossler
and Walter Lee Sheppard, Jr.

CCRM Inc., Havertown, Pa.

The importance of a properly designed floor in the metal-finishing industry cannot be overemphasized. Complex systems and a wide variety of chemicals, all under one roof, are commonly found in metal-finishing plants. The finishing plant floor is subject to punishment because of the continual handling of parts, which results in drips, spills and splashing; the presence of excessive moisture and humidity; and the destructiveness of the thermal shock, mechanical impact, cleaning methods and vibrations involved.

Where spillage and drip occur and adequate protection is not provided, concrete floors are attacked unevenly, and the surface becomes rough. Supports for tanks resting on such floors also become uneven, and tanks may tend to change position slightly, perhaps tipping out of a true vertical position. In shops with automatic plating machines, any such movement can cause the equipment to misalign, scrape the tank sides or hang up.

Three types of protection systems can be specified, depending on the service: corrosion-resistant brick or tile floors, monolithic resinous floors or polymer concrete.

BASE FLOORS

Almost all industrial floors that must support heavy traffic and heavy structural loads are constructed of concrete. The concrete must be structurally sound and strong enough to support the full operating loads. It must be of high strength (generally 3000 psi or better), steel reinforced and homogeneously poured. It must be moist cured (if new) a minimum of 10 days prior to installation of corrosion proofing. It must have a slope toward drains of at least ¼ in./ft, and it must have a screed or wood float finish with a minimum of surface laitance (i.e., a minimum accumulation of fine particles, usually lime or portland cement, on the surface of the concrete).

Old concrete floors must be thoroughly cleaned and free of uneven, broken and badly cracked areas. Chemicals, oils and other contaminants can be removed by detergent acid washing, chipping or sandblasting. Cracks and breaks must be repaired properly before corrosion proofing is started and all weak areas replaced.

Floor drains of appropriate design should be installed or adjusted to the correct elevation with respect to the finished floor (see Fig. 1). The concrete must also be provided with expansion joints in accordance with sound engineering techniques and precautions taken to isolate vibrations, structural members, pump foundations and the like.

CORROSION-RESISTANT BRICK FLOORS

Corrosion proofing a floor by using "acid brick" and a corrosion-resistant mortar is a highly reliable method for protection. This is especially true in places where heavy traffic, harsh chemicals and general abuse of the floor are common.

Impervious Interliner

The first step in construction of a good corrosion-proof brick or tile floor is the interliner or membrane. Tile must be a minimum of 1 in. thick when laid over a membrane. The

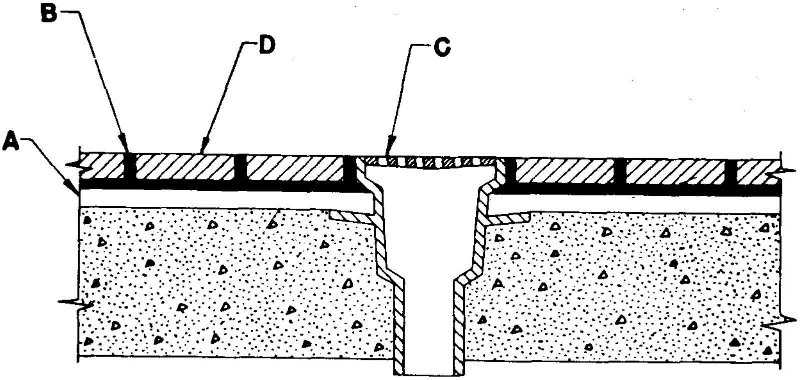

Fig. 1. Typical floor drain construction: (A) ¼-in. asphalt interliner with glass cloth reinforcing and concrete primed with asphalt primer; (B) chemically resistant mortar joints; (C) "Josam" or similar type of floor drain; (D) acid-proof brick, top surface of drain and cover should not be less than 1/16 in. below the surface of surrounding floor.

interliner must be impervious to chemical attack and liquid penetration for the anticipated service. Most such interliners are made of a special hot-applied asphalt. On floor surfaces the interliner is ¼ in. thick and is reinforced with a single ply of asphalt-impregnated glass cloth. It is wise to use two layers of glass reinforcing throughout all trenches, sumps and pits and to keep the membrane in such areas to a minimum thickness of ⅜ in. All membranes must be continuous. An interruption in the membrane will permit liquid to penetrate the substrate at that point.

The clean, dry concrete surface is first brush primed with an acid-resistant compatible asphaltic primer to carry asphalt particles onto the concrete surface to provide better bonding. The primer is allowed to dry for 4 hr or more undisturbed by traffic. The membrane material is then poured hot (cold-applied water emulsions or solvent systems are porous, more permeable and not normally recommended, and this includes trowelled urethane and urethane asphalt putties) over the primed surface and spread with squeegees (*not* mops) in multiple layers to secure the thickness desired (see Fig. 2). Reinforcing is imbedded between the layers of asphalt. The asphalted surface is kept closed to all traffic until the brick or tile is emplaced.

Brick

The type of brick used depends on the service to which the floor will be exposed and must be completely resistant to the full range of chemicals and temperatures anticipated, including all cleaners. The masonry does not in itself act as an impervious barrier to chemical environments. Its primary function is to protect the impervious asphalt interliner from mechanical shock, to prevent continuous flow of chemicals over the interliner and to act as a thermal insulator (see Fig. 2).

Floor brick can be either the buff colored, hard burned, high-silica fire clay type or the red shale, clay type. The buff type has better thermal and mechanical shock resistance and is more porous. Red shale brick is more dense but is not as resistant to the various shocks inherent in heavy-abuse areas. In special instances, where hydrofluoric acid or other acid fluoride compounds are present, carbon brick is recommended.

Corrosion-Resistant Mortars

There is no one mortar suited to all exposures. The mortar must be selected with a good deal of care because, in combination with the brick, it forms the "first line of defense" for the corrosion-proof floor. Today there are seven general types of corrosion-resistant mortars: furfuryl alcohol, phenolic, modified phenolic, silica and silicate, sulfur, epoxy and polyester. (Vinyl ester mortars have chemical resistance roughly similar to that of polyester. Acrylics have similar but not as good chemical resistance as polyesters. Urethanes have resistance to mild acids, mild alkalies and some organics.) Table I shows the mortar types and their resistance to various chemicals common to the finishing industry. The mortar should be used both as the side and bed joints, as in Figure 2. Keeping the brick even and the mortar joints as narrow as possible (on average, ⅛ in.) will produce a better floor. Be careful, however, to leave absolutely no air voids. The curing of the mortar before placing the floor into service should be in accordance with the manufacturer's directions. Note also that the chemical limitations of the mortar should be agreed on between supplier and customer and should be tested according to recognized testing procedures (such as those procedures covered in the standards published by the American Society for Testing and Materials, volume 04.05) to qualify a given specification. Note also that the cure of chemical mortars is affected by moisture and temperature.

Expansion/Contraction Joints

All of the considerations enumerated above will come to naught if expansion/contraction joints are ignored in a brick or tile corrosion-proof oversheating. It is a known fact that acid brick tends to swell in wet services, such as in plating rooms. Therefore, expansion joints are a must if heaving of the floor is to be prevented. Expansion and control joints in the concrete subfloor must, of course, be matched in the brick work. Additional expansion/contraction joints through the brickwork to the asphalt interliner must also be provided so that expansion/contraction joints are not more than 20 ft apart, and use ⅜ in. wide over the entire floor and around all fixed points on the floor, such as equipment foundations, *except* for drains. Where wheeled traffic and/or drum rolling over a brick floor is expected, harder chemically-resistant, expansion/contraction joint material must be used to prevent breaking down the edges of the brick at the joint. Where traffic is no problem, softer expansion/contraction materials may be used, but care must be taken that the chemical expansion/contraction joint material must also be capable of extrusion from the joint if the brickwork swells. Asphaltics are not recommended for use in expansion/contraction joints because of poor resistance to solvents and chemicals common to the finishing industry and poor adhesion to brickwork. In addition, although they squeeze out when the joint closes, they do not drop back into the joint when it opens up again.

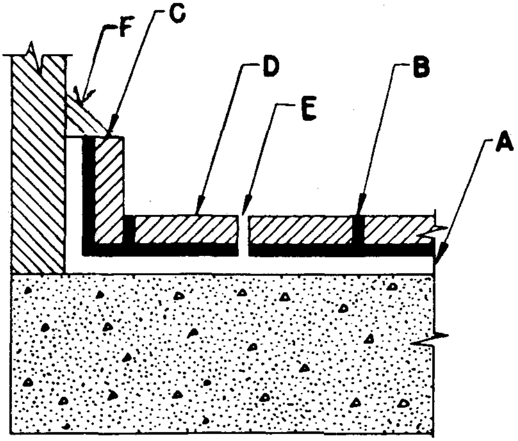

Fig. 2. Acid-proof brick floor with impervious interliner. (A) ¼-in. asphalt interliner with glass cloth reinforcement and concrete primed with asphalt primer; (B) properly selected, chemically resistant ⅛-in. mortar side and bottom joints; (C) cover brick or "soldiers"; (D) acid-proof brick; (E) properly selected, load supporting-type expansion/contraction joint at ⅜ in. wide; (F) cap with mortar or expansion joint sealant to assist drainage.

Table I. Resistance of Chemically-Resistant Mortar Types [a]

	Furfuryl Alcohol	*Phenolic*	*Modified Phenolic*	*Silica and Silicate*	*Sulfur*	*Epoxy*	*Polyester* [f]
Acetic acid	E	E	E	E	E	P–NR	E
Perchloric acid	NR	NR	NR	E	NR	NR	P
Nitric acid	NR	NR	NR	E	G	NR	G
Chromic acid (>1%)	NR	NR	NR	E[b]	P	NR	G
Nitric acid + hydrofluoric acid	NR	NR	NR	NR	G[c]	NR	G[c]
Sulfuric acid							
Strong, 80%+	NR	F	G	E[b]	G	NR	P
Medium strength, 65%	E	E	E	E[b]	E	E	E
Hydrochloric acid	E	E	E	E	E	E	E
Hydrofluoric acid	E[c]	E[c]	E[c]	NR	E[c]	G[c]	E[c]
Phosphoric acid	E	E	E	E[b]	E	G	E
Steam (under pressure)	E	E	E	NR	NR	F	E
Salts, unsaturated							
Acid side	E	E	E	E	E	E	E
Alkaline side	E	P	G	NR	F	E	F
Alkalies							
Strong	E	P	F	NR	NR	E	P
Medium strength	E	P	G	NR	NR	E	F
Chlorinated solvents[d]	E	E	E	E	NR	P	NR
Aromatic hydrocarbons	E	E	E	E	NR[e]	P	NR
Temperature, top limit (°F)	375	375	375	2000	200	225[d]	225

[a] *Note:* An all-purpose mortar, such as the furfuryl alcohols, may perform satisfactorily in services marked "NR" above, provided that the slope of the floor and the regular washdown procedures are such that the liquid chemicals are not allowed to "puddle" for periods of time. Consult the producer for specific recommendations. Epoxy monolithics have served well in chromium plating areas for as long as 10 years, depending on housekeeping.

E = excellent; F = fair; G = good; P = poor; NR = not recommended.

[b] Many sodium silicate mortars are not recommended for floors in sulfuric, acetic, chromic and phosphoric acid service. Use potassium silicates.

[c] Carbon-filled for hydrofluoric acid.

[d] Chlorinated solvents can penetrate poorly laid floors and damage or destroy membranes and interliners.

[e] Resistance is selective.

[f] Basically the same for vinyl esters.

Make drains the midpoint, or point of no movement between expansion joints. Try to place expansion joints near a high point and crosswise, not parallel, to the direction of drainage.

RESINOUS MONOLITHIC FLOORS

Recent developments in plastic technology have spawned some newer materials for use in corrosion proofing a floor. These are thermosetting plastic resins, usually epoxy (epoxy monolithics should not be exposed to sustained temperatures over 140°F or intermittent temperatures above 160°F), vinyl ester or polyester (acrylics and urethanes are also available but are not, in authors' opinion, as suitable for application in plating shops), which are highly filled with siliceous or carbon fillers and are applied by spray or trowel to the concrete subfloors. Such flooring costs, in place, approximately two-thirds of the cost of an acid brick floor and is suitable for use in many areas of the finishing plant. Monolithic floorings have been actively marketed for about 25 years; however, where they are used, great care must be exercised to prevent "puddling" or standing liquids. In continually wet environments, monolithic floors tend to saturate. In acid conditions this can lead to penetration to the substrate and loss of bond.

A resinous monolithic floor is usually applied in a nominal thickness of ¼ in., with a minimum thickness of ⅛ in. Do not accept thicknesses less than ⅛ in. The concrete subfloor must of necessity be relatively smooth (wood float finish), have very high strength, and be pitched toward drains and trenches, with a minimum slope of ¼ in./ft and be free of laitance. Minimum strengths for the concrete should be 3000 psi compressive strength and 300 psi tensile bond at the surface prior to application of the monolithic floor. The concrete must also have a very sound surface because the whole success of application of a resinous monolithic topping rests with the bond of the monolithic to the surface of the concrete. No additives to the concrete, such as curing agents or air-entrainment agents, should be employed without the specific consent of the manufacturer of the monolithic topping. Construction or mechanical joints in the concrete must be carried up through the resinous topping, and a tough, flexible, chemically-resistant expansion joint sealant installed.

Occasionally one notes the offering for finishing room application of a silicate-type monolithic topping. This is not recommended at this time because silicates do not offer dependable protection to concrete floors when exposed to live steam or alkaline materials or to large quantities or running water. They also have high absorption and, if applied without a membrane, can be penetrated by chemicals and the substrate attacked.

Expansion, control joints and other points of movement in the slab must be mated to similar joints in the topping. In addition, stress-relief joints through the topping to the slab must be provided at not more than 20-ft intervals.

The chemical resistance of available monolithics varies greatly. These products can be formulated to have very high or low resistance to chemical attack. The same holds true for their thermal shock and heat resistance.

In the epoxy monolithics there are two general classes. That suitable for platers is the polyamine-cured rigid system, which has a high degree of chemical and wear resistance but low temperature resistance (heat limit approximately 160°F). Polyester and vinyl ester floorings can vary greatly, and systems are being marketed that are flexible enough to withstand heat and thermal shock and still have good chemical resistance, although with narrower limits than epoxies. The writers do not at this time recommend urethane or acrylic toppings.

Epoxies resist nonoxidizing acids, alkalies, salts and solvents. Polyesters will resist oxidizing agents, most all acids, *moderate* alkali concentrations and salts. Carbon fillers must be used in hydrofluoric acid or acid fluoride compound environments. Care must be exercised in the selection of the right monolithic, because these products have been developed for many industries, but only a few are suitable for the strong chemical conditions in the finishing industry. "Or equals" should be verified through recognized testing procedures, as is done with the chemically-resistant mortars previously mentioned. Consideration of whether to use a monolithic or brick floor will depend on how severe the service and what kind of traffic loads the floor is exposed to.

The resinous monolithics should not be used for trenches, pits or sumps, especially where there is any standing "head" of chemical solution. The very nature of a highly filled monolithic does not lend itself to being impermeable enough for this service. The acid brick/membrane construction should be employed in these areas.

In the past few years, premolded plastic trenches have become available in a variety of sizes and are manufactured from a number of different resins, including furans, epoxies, vinyl esters and acrylics. If one of these is used, care must be taken to examine the design of the joints between the sections to ensure that the joints can be made totally liquid-tight and that the design of the top of the walls will provide a liquid-tight seal with the membrane of the floor. Failure to seal either of these two joints completely will result in the eventual undermining of the floor and costly major repairs and downtime before one is even aware of the damage. With regard to selection of the best plastic for plating room service, the furan type has the widest applicability and chemical resistance and should provide the longest life.

POLYMER CONCRETE

There has been much in print about "polymer concrete," and it is likely that some of these materials will be offered to platers for use in floors and trenches. It is therefore important for platers to be aware of both the strengths and weaknesses of these materials.

First, there are basically two different types of materials that are often confused:

1. *Polymer concrete* is a mixture of a resinous or sulfur binder with a silica sand filler and graded quartz (silica) aggregate, containing no portland or calcium aluminate or other hydraulic cement and no calcium or alumina products.
2. *Polymer cement concrete* is a regular concrete composed of portland, calcium aluminate or other hydraulic cement, sand and aggregate of any type, to which has been added a sulfur or resin binder.

The first of these materials has excellent chemical resistance in the range indicated for the resin or sulfur binders (see Table I). Methacrylate polymer concrete in general would parallel the resistances indicated for polyesters but at a somewhat reduced level. The second material is designed primarily for physical strength and resistance to freeze/thaw, but with little difference from regular concrete in chemical resistance. Some suppliers believe that the addition of the resin or sulfur will protect the portland cement in the concrete. Although there is some evidence of an improvement in resistance to weak vinegar and other organic acids, there is insufficient evidence of any substantial difference or improvement in the resistance of the plain concrete to strong inorganic acids, such as hydrochloric, nitric and sulfuric.

In the case of sulfur concrete, platers should be aware of an additional problem. Sulfur cements and sulfur-bearing mortars are *not* recommended for exposure to solutions of copper and beryllium salts. In such exposures a very slow, but progressive, chemical reaction can take place, continuing over several years. Copper and beryllium salts react very slowly with the sulfur in the cement or concrete to form complex and growing sulfides that slowly expand and eventually can disrupt the sulfur mortar or concrete. Test exposures of one- or two-months or even a one-year duration are not meaningful to demonstrate satisfactory service under such exposures.

Two additional limitations on the use of polymer concretes should be kept in mind:

1. They have rather high cure shrinkage characteristics and are very likely to develop cracks, which may be simple crazing or which may extend all the way through the polymer concrete.

2. They have a measurable absorption. Therefore, if a vessel or pit is formed completely of the polymer concrete, and if it is kept at all times full of liquid, with no chance to dry out, the polymer concrete will eventually saturate, and what is on the surface inside will also be on the surface outside the polymer concrete as a "sweat." This will take a rather long time to occur if there is no cracking (only a very small vessel would not show some cracking), and if the polymer concrete is given periodic dry rest periods, it may never happen. Normally, polymer concretes are installed without a membrane under them; however, because of the tendency of the material to develop shrinkage cracks, perhaps as long as one year after installation, the plater who considers such flooring would be well advised to require that a liquid-tight membrane, such as described above, *not* a roofing or waterproofing felt or a polyethylene sheet, be first provided by the installer. Some single-component, water-mix inorganic cements have the capability of being used as an acid-resistant brick mortar, poured or troweled monolithic surfacing or as a pneumatically applied gunite. These cements are silica based. They have exceptional adhesion to concrete, brick and steel and will resist any concentration of any acid (except hydrofluoric and acid fluorides) up to boiling. They should not be exposed to live steam or constantly running neutral or alkaline waters or alkalies. The use of such inorganic cements in monolithic applications may be seen occasionally in all-acid exposures. They are more porous than resin monolithics and can be penetrated by chemicals.

These products should be used with some discretion and should not be used in areas where they are exposed to strong alkalies. The manufacturer must be consulted for proper recommendations and guarantees. Furan resin "concrete" has been employed in chemical service for the past 10 years, including a few areas involving metal finishing. The principal problem noted with this new material has been shrinkage cracking. Applications made over a membrane will resolve fluid penetration; however, the method of sealing cracks as they occur still requires study.

ADJACENT FLOOR AREAS

Concrete floor areas adjacent to plating operating should be given some consideration as to protection or sealing, "tracking" of chemicals via truck or foot traffic into these areas or the very real problem of dusting of the concrete, with resulting contamination of the finishing operation. The following treatments should be considered:

Chemical Surface Conversion

This is usually a magnesium/zinc fluosilicate or a sodium silicate solution scrubbed or mopped into the concrete surface. The free lime in the concrete, which is the cause of dusting, is chemically "tied up," and the surface is densified. This method of protection will minimize dusting but is of no value for resistance to chemical attack. Also, alkali cleaners will damage or reverse such treatments.

Coatings (1⁄18 in. Thick or Less)

Use of epoxy, polyurethane or other chemical- and wear-resistant coatings will provide a dust-free surface and give some chemical protection. The success of any coating is dependent of course on surface preparation, and the user should also expect to perform periodic maintenance on the floor because the coating will wear off or be chipped by traffic, etc.

Sealers

Concrete sealers have been on the market for many years. Some of these are the penetrating type; others act more like a coating. Most of the older types act primarily as dustproofers and have little or no value as chemical barriers; however, there are some new penetrating sealers that have a limited degree of chemical and abrasion resistance.

The use of penetrating sealers is the best method of treating concrete floors adjacent to plating areas because they last longer, give better protection in depth and do not depend entirely on a coating surface for impact and abrasion resistance. Penetrating sealers should be applied to sandblasted or etched concrete and may penetrate up to ¼ in. deep. Because the pores are filled, traffic is borne by the exposed concrete aggregate, whereas the portland cement matrix is covered by a thin layer of the sealer.

It must be thoroughly understood that surface treatments for concrete cannot be substituted for proper acid-resistant construction in the process areas of the plating plant.

SPECIFICATIONS AND TESTING

The original design and any refurbishing of floors should be covered by adequately written specifications. This helps prevent costly mistakes, both from the customer's and the supplier's point of view. All conditions of environment that the floor materials must withstand, such as temperature, traffic load, chemicals, cleanup materials and procedures, should be spelled out explicitly. Materials specified and all materials offered as equal should be verified as meeting the specifications. The applicator should be required to give evidence of the satisfactory completion of three similar jobs within the past two years and agree to place on the job the foreman or lead man who laid one of the reference floors.

Testing, especially for chemical resistance, should be carried out in the chemicals and at the temperature involved. Long-term chemical tests of at least 56 days' duration should be the rule. The tests spelled out in American Society for Testing and Materials (ASTM) Standards should be followed exactly. So-called chemical resistance tests that call for "spot testing" or that are of very short duration should not be considered for qualifying mortars and toppings for the severe chemical environment common to the finishing plant. Physical testing should also be carried out under procedures given in the published standards of ASTM, American National Standards Institute, National Association of Corrosion Engineers, or similar recognized organizations. Installers who request variances or substitutions for specified materials should be required to give long-term warranties for the performance of substitutes.

REPAIRING PLATING ROOM FLOORS

by Walter Lee Sheppard, Jr.

CCRM Inc., Havertown, Pa.

Every plater is faced at one time or another with the problem of repairing or replacing the floor in his or her plating room. The plater wants to do it as quickly as possible so as to get back into production with the least downtime, yet to make a repair that will last. This is particularly important where there is automatic machinery—where plating racks are lowered, timed, and raised in an automatic cycle, and deterioration of the floor can make a tank tilt out of alignment and cause the rack to hang up on a tank wall.

In the past, small plating shops have made do at the start with an existing floor in a converted residential building where the floor is often of wood. Consider the problem that may exist with the heavy standing load of liquid-filled tankage on floors that were designed to support people and their furniture. The first thing to do is to check the beams and supports to be certain that their design is adequate and condition sound. A local contractor or engineer friend can do this for you at minimum expense and it is of key importance to your success. The engineer should consider inadequate any floor that will deflect visibly under the load that you expect to place on it. It is acceptable to *feel* movement as long as you cannot see it.

If the tanks are placed so that liquid dragout on the work or racks drips on the wood floor, no amount of washdown can save the floor from serious damage. If you have tried operating without a protective surfacing over your floors, you have already discovered this, and you may have also discovered damage on the floor below caused by leaking from the operations.

The best protection, if your floor supports are strong enough, is to cast a 4-in. reinforced concrete slab on top of the existing floor, and apply a preferably thin (1¼-in.) acid-brick floor over the concrete, employing a hot asphalt membrane between the concrete and the brick. (See article on Acid Resistant Floor Construction elsewhere in this *Guidebook.*) The second choice is a ¼-in. trowelled epoxy floor surfacer over the concrete. Be careful to install a proper drain in the concrete and to slope the surface to it. A polymer concrete may be an acceptable substitute for both the concrete and the topping.

If the existing floor is unable to support the weight of the concrete in addition to that of the loaded tanks, all is not lost. There remains a compromise, which if properly installed and maintained, can last for many years. Clean the old wood floor thoroughly, replacing any damaged or badly worn timber. Then, bring in a large sander and run it over the old floor to get a completely uniform surface. Now nail down over the old wooden floor sheets of ⅝-in. thick or thicker marine plywood, butting all the edges tightly and smoothly together, and countersinking all nails. Over the marine plywood apply, as first choice, a hot asphalt membrane and 2¼-in. (not thinner) acid-brick. Expansion joints should be placed at 15 ft. intervals or less.

If this is beyond the weight limitations, then the second choice is a ¼-in. thick epoxy surfacer. If the epoxy is used, place expansion joints around the periphery of every sheet of plywood, matching the expansion joints to the cracks between that sheet and the next. Both types of floors have served successfully for years over this type of substrate, provided that they are properly cared for and maintained. This means repair *as soon as* a crack appears. Do not delay.

If the floor under the duck boards is plain concrete, or concrete protected only by a paint coating, and has been subject to spills and drips for a long time, the damage will be extensive and will cover the entire working area. Under such circumstances, there may be such structural damage to the building as to make repair a waste of money, or so much plating waste may have penetrated the soil under the floor as to cause problems with the EPA. In either case, excavation of the diseased concrete and of all badly contaminated soil must be accomplished before the work area can be rehabilitated.

Fresh concrete, properly designed and reinforced, is then installed, with the reinforcing tied in solidly to the reinforcing in the walls and elsewhere in the building. Before considering measures to protect the new concrete from experiencing a repetition of this damage, the concrete must be permitted to cure, free of traffic, or the spillage of any corrosives. The use of type III Portland cement in the mix will provide acceptable strength in four days. However, faster strength development and readiness to accept the corrosion resistant surfacing can be more quickly supplied by the use of a super plasticizer in the concrete, while simultaneously retaining "slump" at a *maximum* of 4 in. With the appropriate amount of super plasticizer added and using type I Portland, full strength (not just a workable percentage) will be developed in 72 hours, and with a reduction of 30–32% of water demand. In 28 days, the concrete will develop a 190% design strength and the low absorption of 5–6% as compared with "normal" concrete absorption of approximately 20%.

If this route is followed, the new concrete surface should be decreased by the thickness of the surface protection planned. With an acid brick, this would be 2⅝ in. (including ¼ in. for an asphalt membrane plus 2¼-thick shale brick with a ⅛-in. bed joint of mortar). Lesser thickness of brick may be used if desired, but labor and material costs will not be much different if 1⅛-in. red shale splits or 1¼-in. pavers are used, and the delivery time may be longer. Do *not* go under 1 in. thickness and do not use quarry tile. With a polymer concrete, the same general construction may be accomplished.

If a ¼-in. epoxy monolithic topping is used, the change in elevation is slight, but the ¼-in. slope to the foot required in this case may affect the location of services if the original floor is dead flat.

If the floor of the shop is new, or if the shop has only been operating for a short time without floor protection, it would be wise to arrange for floor protection at the earliest available time, closing off and working on each individual area in turn. If the work is to be done in this manner, the least downtime will be experienced if castable floor surfaces 1- to 2-in. thick are planned to cover the existing floor. This will mean elevating all services, electrical and plumbing, in each area. That work may be done at the same time the floor contractor is cleaning the surface of the floor that is to be elevated, before applying the new surfacing.

Though an acid brick floor properly selected and installed is the best protection you can get, it would require at least double the downtime of the monolithic surfacing and would necessitate further elevation of the services.

Inasmuch as no castable monolithic or polymer concrete can tolerate exposure to the full range of corrosives in a plating shop, it is important to plan to segregate your operations and assign specific areas for specific exposures. All chrome work, where there is a possibility of chromic acid spillage, and all areas where nitric acid over 5% concentration may be spilled, should be grouped and, if possible, done simultaneously. A castable polyester or vinyl ester mortar with acid brick, or a polymer concrete made from these same resins, is the type of material indicated in such a case.

In areas where any acids other than hydrofluoric are used and/or where caustics may be spilled, a furan concrete may be selected. In areas where spills may consist of strong bleach, weak acids other than hydrofluoric, mixed perhaps with any combination of caustics, epoxy concretes are indicated.

Where hydrofluoric acid or strong alkali exposure are anticipated, the same resins may be used as just mentioned, but the filler must be carbon, such as crushed anthracite.

Recently, there has been an intensified interest in the use of sulfur concretes in plating shops. The plater should be warned, however, that copper and beryllium salts react very slowly over a period of a year or more with sulfur concrete and sulfur cements to form expanding growth salts, a reaction that can eventually destroy the floor. In such areas, brick mortared with sulfur cement or a sulfur concrete obviously should not be used. It should also be noted that sulfur mortars and concretes can be injured by exposures for any extended periods to live steam.

A great many sales pitches and much advertising accompanied by case histories have appeared in technical literature over the past decade, pushing the use of silicate castables as floors in chemical areas. They often claim satisfactory operation in areas of exposure to everything except hydrofluoric acid and acid fluorides, within a pH range 0–9, sometimes even 0–12.

The plater should receive these claims with caution. Although it is absolutely true that silicate castables and silicate concretes have outstanding resistance to all acids except hydrofluoric (and acid fluorides), when subjected to alkalis in a continuous exposure they will be quickly damaged and, in a short time, destroyed. Silicates resist organic materials with pH ranges as high as 9, and for a short period of time the bases of weak alkali metals. Even very dilute solutions of hydroxides of the strong alkali metals (sodium, potassium, and so on) attack them very rapidly. Continued exposure to live steam and to running hot neutral or alkaline water will wash them out.

Further, silicate castables (or silicate concretes) have far higher fluid absorption than other polymer type concretes. To be used satisfactorily in plating service, they should only be employed over positive liquid seal membrane. Without the membrane, liquids standing on them or passing over them will eventually penetrate to the substrate below, and although they may not damage the silicate castable, the penetrating materials still have the power to damage the substrate. With the limitations just stated, silicate castables may be considered for use in a few specific areas.

Note that all polymer concretes are subject to hairline cracking over long periods of time. If a crack should occur it must be repaired promptly if the floor is to survive.

CHEMICAL-RESISTANT TANKS AND LININGS

by C. E. Zarnitz

Atlas Minerals & Chemicals Inc., Mertztown, Pa.

The dominant and most economical construction materials used in the metal-finishing industry are steel and concrete. Unfortunately, both of these materials are highly susceptible to corrosive attack from many of the chemicals used in the metal-finishing industry. Pickling and plating chemicals are highly corrosive and, without proper protection, the life span of steel and concrete is limited. Tanks and tank linings must be capable of:

1. resisting attack from organic and inorganic, oxidizing and nonoxidizing chemicals at varying concentrations, as well as from various solvents;
2. resisting broad thermal variances including thermal shock;
3. resisting weather extremes because economics dictate that very large storage and waste treatment vessels be located outdoors;
4. resisting physical abuse that accompanies processing strip, heavy parts, shapes and castings; and
5. maximizing performance, value, and ease of maintenance.

TANKS AND LININGS

The type of tanks that have excelled in the metal-finishing industries include lined carbon steel; lined, precast, or poured-in-place concrete; precast or poured-in-place polymer concrete; self-supporting plastics, i.e., thermosets and thermoplastics; and alloys.

The success of steel or concrete-lined tanks is predicated on good engineering design of the structural shell. The ultimate success of the lining, besides good engineering design, is predicated on the finish and structural integrity of the substrate, as well as on the skills and proficiency of the applicator. If the structure cannot sustain the stress imposed by the process, lining failure is imminent. Similarly, plastic or alloy tanks will fail if good design engineering has been compromised.

Carbon Steel Tanks

When fabricating carbon steel tanks for subsequent lining, the following are important:

1. Minimum number of pieces and sufficient reinforcement must be used to prevent bulging when subjected to optimum process stress.
2. Vertical reinforcing is preferred to horizontal. Ledges are eliminated, thus minimizing potential for drag-out to hang, concentrate, and corrode the vessel from the "outside-in."
3. Welds to receive lining are to be solid and continuous.
4. All corners are to be ground to a minimum radius of ⅛ in.; no sharp right angles.
5. Exterior reinforcing members may be skip welded.
6. All body seams must be butt welded true and flat with variation on alignment not to exceed 25% of plate thickness and in no case more than ⅛ in.
7. All outlets to be flanged.
8. Interior of vessel must be free of weld splatter, pits, deep gouges, and all welds ground smooth.

The following typical outlet and weld details are suggested when fabricating carbon steel that will be lined with various types of linings (see Figs. 1 and 2).

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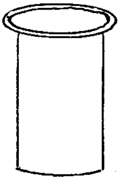

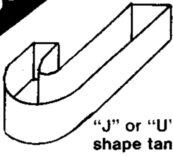

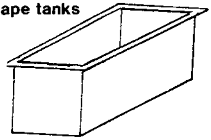

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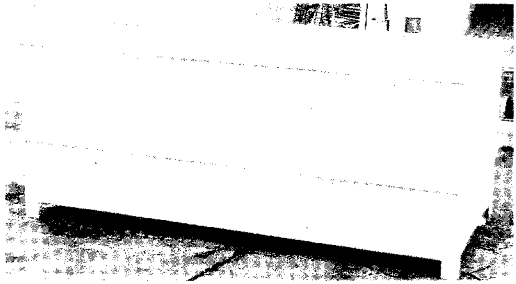

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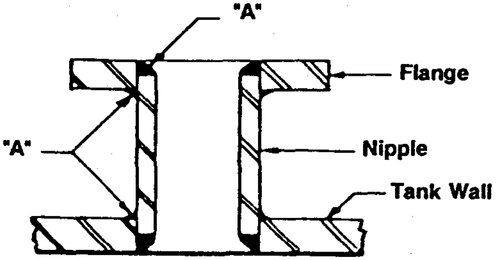

Fig. 1. Flanged nipple outlets in tanks and covers. Welds "A" should be burned into plate so welds meet from opposite sides, thereby excluding air pocket. Welds must be peened and ground smooth.

Stainless Steel Tanks

Stainless steel tanks can be compared to plastic tanks in the respect that they are solid steel, thus eliminating the need to protect a vulnerable exterior from fumes and splash. Stainless steels generally are classified as straight iron-chromium alloys and iron-chromium-nickel alloys. In the metal-finishing industry, the iron-chromium-nickel alloys, i.e., the 300 series appear to be the most popular. Types 302, 304, 321, and 347 are considered to be generally equivalent in chemical resistance.

The stainless steel alloys exhibit excellent resistance to such oxidizing acids as nitric and chromic. They have virtually no resistance to hydrochloric and hydrofluoric acids.

The vulnerability of stainless steels to halogenated acids is easy to understand when you recognize that pickling solutions for stainless steel are acids such as hydrochloric and hydrofluoric and various combinations of nitric and hydrofluoric. Figs. 3–5 provide typical outlet and weld details for the fabrication of tanks.

Portland Cement Concrete Tanks

Concrete tanks are acceptable so long as good design engineering is practiced and includes: sufficient reinforcement to prevent buckling and cracking; minimum 3,000 psi

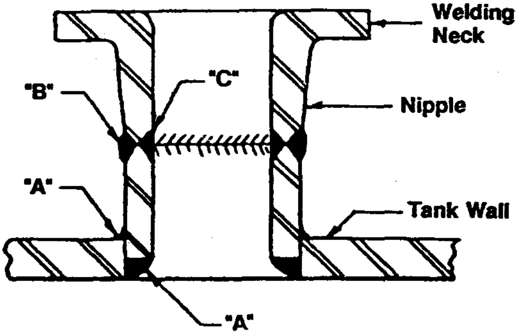

Fig. 2. Flanged nipple outlets when welding neck is specified. Weld "B" to be laid in V in beads not to exceed 3/16-in. deep. After "B" is built up above plate outside, the inner surface must be routed out sufficiently to remove all scale and slag. Weld "C" is to be built up above the surface of plate, peened, and ground flush.

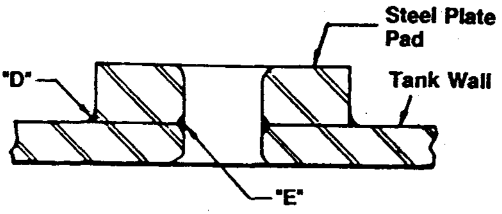

Fig. 3. Pad outlets. Weld "D" is the same as "A," except penetration is not required. Drill two 1/8-in. diameter holes, 180° apart, through weld for vent. Weld "E" plate must be bevelled distance equal to thickness of tank wall. Weld is to be built up above the surface of plate, peened and ground smooth and flush with plate.

compressive strength after 28 days; smooth, monolithic interior free of ridges, depressions, honeycomb, form marks, etc.; freedom from contaminants and additives, i.e., form release agents, air entraining agents, etc.; and hydrostatically tight and waterproofed on the exterior if located below grade.

Self-supporting plastic and stainless steel tanks must comply with similar structural mandates as those enumerated for carbon steel and Portland cement concrete.

Polymer Concretes

Polymer concretes are a generation of materials that have rapidly matured because of their outstanding chemical resistance and physical properties. They are not to be confused

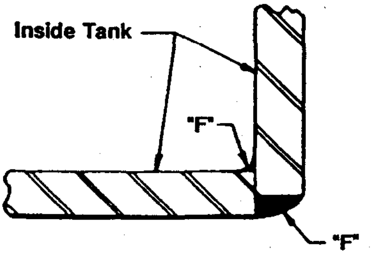

Fig. 4. Corner of rectangular tank. Weld "F" should be burned into plate so welds meet from opposite sides, thereby excluding air pockets. Welds must be peened and ground flush.

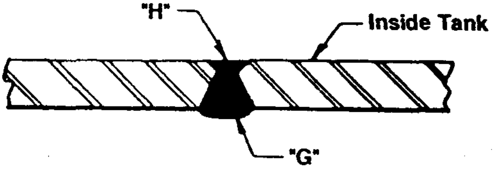

Fig. 5. Butt joint. Weld "G" to be laid in V in beads not exceeding 3/16-in. deep. After "G" is built up above plate on outside, the inner surface must be gouged out sufficiently to remove all scale and slag. Weld "H" is to be built up above the surface of plate, peened and ground flush.

Table I. Typical Physical Properties of Polymer Concretes

Property	*Test Method*	*Typical Value*
Tensile strength, psi (MPa)	ASTM C 307	1,000–2,000 (7–14)
Compressive strength, psi (MPa)	ASTM C 039	10,000–12,000 (70–82)
Flexural strength, psi (MPa)	ASTM C 580	2,000–4,000 (14–28)
Linear shrinkage, %	ASTM C 531	<0.1
Density, lb/ft^3	ASTM D 792	130–145 (2.1–2.3)
Water absorption, %	ASTM C 413	<0.1
Maximum use temperature, °F(°C)		
Continuous	—	150 (66)
Intermittent	—	200 (93)
Thickness, in. (mm)	—	0.5 (13)

The chemical resistance of polymer concretes is similar to their synthetic resin lining system counterparts as indicated in Table VII.

with Portland cement concrete or polymer-modified Portland cement concrete. The only similarity to Portland cement concrete or polymer-modified Portland cement concrete is the use of properly graded and sized aggregate in order to optimize workability and physical properties of the composition. Polymer concretes utilize inert siliceous aggregates with binding systems based on such resins as furan, epoxy, polyester, vinyl ester, and acrylic. (See Table I for typical physical properties of polymer concretes.)

The advantages to be derived from polymer-modified Portland cement concrete when compared with Portland cement concrete are:

1. Permits placement of concrete in thinner cross-sections.
2. Excellent bonding to existing concrete substrates.
3. Increased impact resistance.
4. Reduced porosity.
5. Faster set and cure.
6. Improved resistance to salt. It does not improve resistance to chemicals.

Polymer modifiers are generally based on various resins and latexes, such as natural rubber, styrene-butadiene, acrylic, polyvinyl acetate, epoxy, and urethane.

LININGS

There are a host of lining materials available for protecting concrete and steel. The three basic types are glass-fiber-reinforced sheet and molten asphaltics; sheet rubber, plastics, and elastomers; and reinforced and nonreinforced ambient-cured synthetic resin systems.

Conspicuous by its absence from this list is protective coatings. This is not to say they can't be used; however, 60 mils is usually considered to be a minimum acceptable thickness for a material to be considered a tank lining. If a coating can be economically applied (initial cost and longevity) to a minimum thickness of 60 mils, free of pinholes and holidays, and can resist the process chemicals and temperatures as well as physical abuse, consideration should be given to their use. Generally speaking, coatings are used for fume and splash protection and not necessarily for total immersion process applications.

Asphaltic linings are equally appropriate for application to concrete and steel. The hot-applied, molten materials, as well as sheet stock can be used on concrete tanks. For steel tanks, glass-fiber-reinforced sheet is the most desirable. Both types of asphaltic linings, sheet and molten, are seldom, if ever, used without being further protected with a chemical-resistant brick lining. Without further protection from a brick sheathing, these linings can cold flow and be easily damaged from impact, abrasion, and thermal excursions. Masonry sheathings

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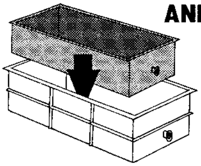

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Table II. Physical Properties of Asphaltic Linings

	Value	
Property	*Type A*	*Type B*
Softening point, °F (°C)	200–225 (93–107)	250–275 (121–135)
Ash, max., %	0.5	0.5
Penetration		
77°F (25°C), 100 g—5sec.	38	18
115°F (46°C), 50 g—5sec.	75	27
Chemical resistance	Very good	Very good

provide a rugged, chemical-resistant insulating barrier for protection of asphaltic as well as other types of linings. The physical properties and the chemical resistance of asphaltic linings are shown in Tables II and III, respectively.

Adhesive-bonded sheet linings, such as various plasticized plastics, rubbers and elastomers are most commonly used for steel tanks. Successful applications have been made on concrete; however, it is not the most desirable substrate on which to bond and cure many of these systems. The physical properties and the chemical resistance of sheet linings are shown in Tables IV and V, respectively.

Mechanically bonded rigid plastic linings for precast and poured-in-place concrete tanks are a relatively new concept. Instead of bonding with adhesives, this system utilizes anchor studs sonically welded to the back of the sheet for locking or mechanically bonding the sheet to the concrete.

Ambient temperature-cured, spray- and trowel-applied *synthetic resin lining systems* are based on the following resins: furan, epoxy, polyester, vinyl ester, and urethane.

These systems are entirely appropriate for application to steel and concrete. They have also been successfully applied to wood, certain plastics, and various metallic substrates. These

Table III. Chemical Resistance of Asphaltic Linings

Medium	*Type A*	*Type B*
Aluminum salts	R	R
Cadmium salts	R	R
Chromic acid, to 10%	R	R
Copper salts	R	R
Gold cyanide	R	R
Hydrochloric acid	R	R
Hydrofluoric acid	C	C
Iron salts	R	R
Magnesium salts	R	R
Nickel salts	R	R
Nitric acid, to 20%	C	C
Perchloric acid	NR	NR
Phosphoric acid	R	R
Sodium chloride	R	R
Sodium cyanide	R	R
Sodium hydroxide, to 30%	R	R
Sodium salts	R	R
Sulfuric acid, to 50%	R	R
Trichloroethylene	NR	NR
Trisodium phosphate	C	C
Zinc salts	R	R

C, conditional; R, recommended; NR, not recommended.

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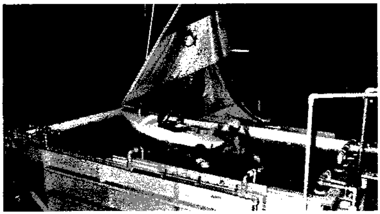

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Table IV. Physical Properties of Sheet Linings

Type	Temperature Resistance Max., °F (°C)	Chemical Resistance
Natural rubber		
Soft	150 (66)	Very good
Semihard	180 (82)	Very good
Hard	180 (82)	Very good
Neoprene	180 (82)	Very good
Butyl rubber	185 (85)	Very good
Chlorobutyl rubber	185 (85)	Very good
Polyvinyl chloride		
Plasticized	150 (66)	Excellent
Plasticized rigid (2 ply)	150 (66)	Excellent
Chlorosulfonated polyethylene	275 (135)	Very good
Fluorocarbons	450 (232)	Excellent

lining systems utilize such filler reinforcements as flake glass and mica. Fabric reinforcements such as fiberglass are the most common; however, synthetic fabrics are used where fluorides are present.

These linings are extremely versatile and can be applied by maintenance personnel with skills in the painting and masonry trades. Most manufacturers of these lining systems provide training programs for plant maintenance personnel. The physical properties and the chemical resistance of ambient-cured synthetic resin lining systems are shown in Tables VI and VII, respectively.

Table V. Chemical Resistance of Sheet Linings

Medium	1[a]	2	3	4	5	6
Aluminum salts	R	R	R	R	R	R
Cadmium salts	R	R	R	R	R	R
Chromic acid, to 10%	NR	NR	NR	R	R	R
Copper salts	R	R	R	R	R	R
Gold cyanide	R	R	R	R	R	R
Hydrochloric acid	R	NR	R	R	R	R
Hydrofluoric acid	R	NR	R	R	NR	R
Iron salts	R	R	R	R	R	R
Magnesium salts	R	R	R	R	R	R
Nickel salts	R	R	R	R	R	R
Nitric acid, to 20%	NR	NR	R	R	C	R
Perchloric acid	NR	NR	NR	C	NR	R
Phosphoric acid	R	R	R	R	R	R
Sodium chloride	R	R	R	R	R	R
Sodium cyanide	R	R	R	R	R	R
Sodium hydroxide, to 30%	R	R	R	R	R	R
Sodium salts	R	R	R	R	R	R
Sulfuric acid, to 20%	R	R	R	R	R	R
Trichloroethylene	NR	NR	NR	NR	NR	R
Trisodium phosphate	R	R	R	R	R	R
Zinc salts	R	R	R	R	R	R

R, recommended; C, conditional; NR, not recommended.

[a] 1 = natural rubber—all grades; 2 = Neoprene; 3 = Butyl and chlorobutyl; 4 = polyvinyl chloride; 5 = chlorosulfonated polyethylene; 6 = fluorocarbons.

Table VI. Physical Properties of Ambient-Cured Synthetic Lining Resin Systems

	Temperature Resistance[a]	
Type	*Max.*, °F (°C)	*Chemical Resistance*
Furan	125 (52)	Excellent
Epoxy	160 (71)	Very good
Polyester	180 (82)	Very good
Vinyl ester	160 (71)	Very good
Urethane	150 (65)	Good

[a] Suggested limit without a masonry sheathing.

The tables shown above all provide the design and corrosion engineer with basic information on the various lining systems discussed. They identify specific corrosives encountered in various metal-finishing operations. Enumerated are each of the various types of linings and a general recommendation for its use in the particular medium. It is recommended that the acceptability of specific linings, in specific media, be verified with the manufacturer.

Chemical-Resistant Brick and Tile Linings

Historically, chemical-resistant brick and tile linings go back approximately 100 years, paralleling the development of sulfuric acid, various dyestuffs, and explosives.

The use of masonry construction has grown in the basic steel, metal-working, and metal-finishing industries. Chemical-resistant masonry sheathings are not to be construed as hydrostatically tight tank linings. They are, in fact, porous, and consequently must be

Table VII. Chemical Resistance of Ambient-Cured Synthetic Resin Lining Systems

Medium	*1*[a]	*2*	*3*	*4*	*5*
Aluminum salts	R	R	R	R	R
Cadmium salts	R	R	R	R	R
Chromic acids, to 10%	NR	NR	R	R	C
Copper salts	R	R	R	R	R
Gold cyanide	R	R	R	R	R
Hydrochloric acid	R	R	R	R	R
Hydrofluoric acid	R[b]	R	R	R	C
Iron salts	R	R	R	R	R
Magnesium salts	R	R	R	R	R
Nickel salts	R	R	R	R	R
Nitric acid, to 20%	NR	NR	R	R	R
Perchloric acid	NR	NR	C	NR	NR
Phosphoric acid	R	R	R	R	R
Sodium chloride	R	R	R	R	R
Sodium cyanide	R	R	R	R	R
Sodium hydroxide, to 30%	R	R	Bis A Type	R	R
Sodium salts	R	R	R	R	R
Sulfuric acid, to 50%	R	C	R	R	R
Trichloroethylene	R	NR	C	NR	NR
Trisodium phosphate	R	R	Bis A Type	R	R
Zinc salts	R	R	R	R	R

R, recommended; C, conditional; NR, not recommended.

[a] 1 = furan; 2 = epoxy; 3 = polyester; 4 = vinyl ester; 5 = urethane.

[b] Carbon filled materials and/or final application with synthetic fabrics.

Table VIII. Chemical Resistance of Structural Plastics

Medium	*Polyvinyl Chloride*	*Polyethylene*	*Polypropylene*
Aluminum salts	R	R	R
Cadmium salts	R	R	R
Chromic acid, to 10%	R	R	R
Copper salts	R	R	R
Gold cyanide	R	R	R
Hydrochloric acid	R	R	R
Hydrofluoric acid	R	R	R
Iron salts	R	R	R
Magnesium salts	R	R	R
Nickel salts	R	R	R
Nitric acid, to 20%	R	R	R
Perchloric acid	R	C	C
Phosphoric acid	R	R	R
Sodium chloride	R	R	R
Sodium cyanide	R	R	R
Sodium hydroxide, to 30%	R	R	R
Sodium salts	R	R	R
Sulfuric acid, to 50%	R	R	R
Trichloroethylene	NR	NR	NR
Trisodium phosphate	R	R	R
Zinc salts	R	R	R

C, conditional; R, recommended; NR, not recommended.

considered as chemical, physical, and thermal barriers for protecting membranes installed behind these sheathings. Brick sheathings contribute to the longevity of tank linings by offering additional chemical, thermal, and physical protection. They are excellent insulating barriers and, consequently, can be considered as energy savers.

PLASTIC TANKS AND LININGS

There are a multitude of plastics available for solving corrosion problems in the metal-finishing industry. The more popular and cost effective are polyvinyl chloride (PVC), Type I; polypropylene (PP); linear polyethylene (PE); and fiberglass-reinforced plastics (FRP).

All of these plastics have been successfully used as self-supporting tanks and "drop-in" tank liners for process and storage applications. The thermoplastics (PVC, PP, and PE) are being used for mechanical bonding to concrete for similar applications.

Polyvinyl chloride is one of the oldest proven plastics for fabricating highly chemical-resistant structures. (See Table VIII for the chemical resistance of structural plastics.) Type I PVC is one of the best plastics available for resistance to a multitude of strong oxidizing environments up to its thermal limitation of approximately 150°F (66°C).

Type I PVC has outstanding structural integrity attributable to its high tensile, compressive, and flexural properties. It is one of the easiest plastics from which to construct tanks, tank liners, dipping baskets, and other storage and process equipment. PVC is easily thermoformed, cut, drilled, tapped, machined, and welded, consequently, making it an excellent, versatile, and cost-effective material from which to fabricate corrosion-resistant equipment.

Polypropylene has arrived. Its popularity is attributable to its excellent chemical resistance and surpasses PVC because of its superior physical and thermal resistance. It is available as flame and nonflame retardant homopolymer and copolymer sheet stock. Polypropylene utilizes fabricating techniques similar to those used for PVC. Small tanks for pickling and plating, large tanks for continuous strip pickling lines, and pickling line covers have been fabricated of polypropylene. These and similar fabrications are enjoying an enviable record of success in challenging chemical and physical applications.

Linear polyethylene fabrications have performed well in the small-parts metal-finishing industry because of their low absorption, high chemical resistance, and outstanding resistance to impact. They do not possess the rigidity and flexural capabilities of PVC or PP and, consequently, the fabrications are significantly smaller. A new generation of PE is making significant inroads into the finishing industry. Crosslinkable, high-density PE for rotational molding is being used for tanks of 5–10,000-gal capacity. These new resins exhibit excellent physical properties and good resistance to weathering. Applications for the most part have been indoor and outdoor storage tanks and portable receiver tanks.

Fiberglass-reinforced plastics have been successfully used for a multitude of applications for many years. The earliest fabrications utilized furan and phenolic resin binder systems. The more popular resin binder systems in use today are polyester, epoxy, and vinyl ester.

The success of FRP structures is substantially predicated on the proper choice of resin and hardener system most inert to the environment to which the fabrication will be subjected. It is not enough to request an FRP tank, any more than it is to request a flake-glass-reinforced polyester tank. It is important to either provide the fabricator with all chemical, thermal, and physical information pertinent to the process in order that the proper resin and hardener system might be selected, or to have in-house technical competency capable of making the proper selection of the resin-hardener system from which the manufacturer can fabricate the desired equipment.

There are numerous polyester resins available; however, for aggressive corrosion environments, such as high concentrations of alkalies and a broad range of acids, the bisphenol-A fumarate resin is the best recommendation.

Vinyl esters are epoxy-resin-based, thermosetting resins that provide chemical resistance similar to that of bisphenol A polyesters. They are considered to be slightly better in high concentrations of alkaline hypochlorites than the bisphenol A polyester. Vinyl esters exhibit outstanding physical properties, i.e., tensile, flexural, and elongation that are normally associated with epoxies.

The chemical resistance and physical properties of epoxy resins are functions of the resins, but equally important, they are very much functions of the curing systems employed.

Aliphatic and aromatic amine curing systems impart better chemical resistance to epoxy resins than do polyamide curing agents. Polyamides, however, impart better impact resistance to epoxies than do aliphatic or aromatic curing systems.

The intention of these three examples of the resin systems utilized for constructing fiberglass-reinforced tanks and tank linings is to point out the necessity of knowing the chemistry of the system, or relying on reputable manufacturers to provide the technology required to make the best selection to fulfill end use requirements.

Where the chemistry of these various systems contributes substantially to the physical properties of the structure, the most profound influence on physical properties is derived from the proper design and use of various reinforcing mediums, i.e., glass fibers, glass cloth, roving, mat, veil, etc. Consult reputable manufacturers for proper design consistent with the end-use mandates for chemical, thermal, and physical properties.

The chemical resistance of FRP is comparable to the chemical resistance data shown in Table VII. Table VIII summarizes the chemical resistance of PVC, PE, and PP.

The mechanically bonded thermoplastic lining system previously described circumvents many of the limitations inherent in some plastics, as well as coating, and many other elastomeric and resin lining systems. The sonically welded anchor studs are of the same plastic as the sheet and are placed at approximately 2–3 in. on centers. Sheet thickness and anchor stud density provide the rigidity necessary for a successful thermoplastic lining application. The studs, being of the same plastic as the sheet, ensure thermal and physical property similarity. The lining system is equally appropriate for new and existing concrete, as well as for salvaging used steel tanks. Upon removal of the concrete forms and the welding of all joints, utilizing thermoplastic welding techniques, spark testing is used for quality assurance of the lining.

The system is available in a single- or double-wall system to ensure compliance with the most rigid of environmental mandates. Leak detection systems are available and are integral with the lining system.

DC POWER SUPPLIES

by Christopher C. Smith and Peter Cambria

Rapid Power Technologies, Brookfield, Conn.

RECTIFIER OVERVIEW

Rectifiers were introduced to the surface-finishing industry over a half century ago to replace rotating DC generators. Rectifiers have a major advantage in that they have few, if any, moving parts, which results in significant decreases in maintenance and downtime. Today, rectifiers are one of the most reliable and efficient means of power conversion, and nearly all surface-finishing rotating generators have been replaced.

A rectifier can be divided into three major components: a main power transformer, a regulating device to control the DC output, and a rectifying element to convert the incoming AC to output DC. A rectifier also contains auxiliary components, such as control electronics and cooling.

Main Power Transformer

The main power transformer receives line voltage and steps it down to a suitable but unregulated AC voltage. To produce a transformer of the highest efficiency and reliability, three major design factors must be considered. First, all conductors must consist of electrolytically pure copper. Second, the core laminates must be made from low-loss, high-quality transformer steel. Third, extremely high-quality, high-temperature insulating material must be utilized. If the quality of any of these areas is compromised, transformer efficiency and longevity will be sacrificed.

In a high-quality transformer, electrolytically pure copper is used to wind the transformer coils, with insulating material located between each conductor. Once wound, the coils are vacuum impregnated with a high-temperature varnish, and all terminals are then silver brazed. The coils are then placed onto the core.

The transformer core is constructed from low-loss, grain-oriented silicon transformer steel. The steel is cut into the proper lengths and single stack laminated to form the core structure. If a great deal of attention has not been paid to the construction of the core, there will be air gaps between the laminations. This will decrease the transformer's ability to handle magnetic flux, resulting in a transformer with less efficiency.

The majority of transformer power losses is the result of excessive temperatures. The only way to avoid this condition is through proper engineering. This includes designing for low-current densities in the windings, low-flux density in the transformer core, and of course, ensuring proper transformer assembly.

Quality transformers are manufactured in this manner. Unfortunately, improper transformer design or construction is not always visible to the naked eye. A conservatively designed quality transformer will look physically similar to a lesser quality transformer. Because the differences lie in the design and materials, the effect will only become apparent during operation. A higher quality transformer will run 10 to 15% cooler. A transformer operating at lower temperatures will have a much higher efficiency and greater longevity. Although the manufacturing cost is higher on the more efficient unit, the payback for the additional expense is relatively short. Most manufacturers will guarantee a well-designed transformer for 5 years; however, such well designed transformers will typically operate for a minimum of 15 years without problems.

Rectification and Regulation

The silicon diodes used in rectifiers are the simplest and most reliable rectifying devices available. Silicon, when properly treated with certain elements, allows current to flow in one

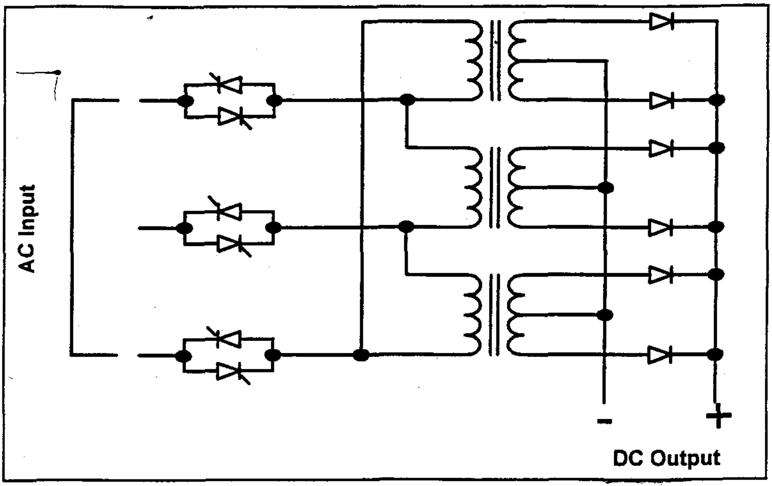

Fig. 1. Primary thyristor.

direction only. When a silicon diode is hermetically sealed, it becomes completely impervious to external conditions, making it capable of withstanding the harsh environments commonly found in metal-finishing facilities.

Another silicon device that is instrumental of today's rectifiers is the silicon-controlled rectifier, commonly known as a thyristor or silicon-controlled rectifier (SCR). The thyristor is basically a silicon diode that will conduct only in one direction and only when a signal is applied to a terminal on the thyristor known as a "gate." In some instances, the thyristor functions as a regulating element, whereas in others, it acts as both a rectifying and a regulating device.

In the primary thyristor configuration, illustrated in Fig. 1, thyristors are connected between the incoming voltage source and the transformer. In this design, a thyristor operates at a relatively high voltage and low current. Generally, all thyristors have a fixed forward voltage drop across them. This drop ranges from 1 to 1.5 V. When the highest quality thyristors are used as primary elements, with an input of 230 or 460 V, the efficiency of the thyristor network is greater than 99%.

In the primary thyristor configuration, the thyristor is solely used to vary the AC supply voltage from zero through maximum. In order to make a fully regulated controller, each phase of the three-phase input must have two thyristors connected back to back, as shown, and their gates must be symmetrically triggered.

The regulated voltage is then fed from the thyristors to the isolation transformer, which converts the incoming high voltage/low current to a lower voltage and a higher current. From the transformer, you now have the desired output voltage and current, but it is still in an AC form. It is here that the silicon diodes are utilized. The function of the diodes, as stated earlier, is to allow conduction of current in only one direction. When the diodes are used, as shown in Fig. 1, they will rectify the transformer output and provide DC.

Another method is to place the thyristors on the secondary side of the transformer, as shown in Fig. 2. This is known as a secondary thyristor design. In this configuration, the thyristors perform both the regulation and rectification operations, and no diodes are required.

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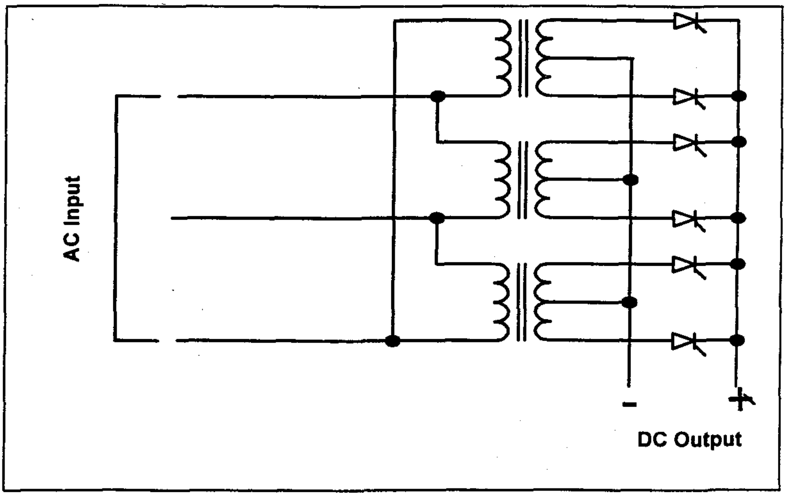

Fig. 2. Secondary thyristor.

Either design can provide the desired DC output, and although each method has its advantages and disadvantages, the cost is usually the determining factor.

The advantages of the primary method are as follows:

Soft start—Because the controlling element is in the primary side of the transformer, it can control the inrush current to the transformer.

Efficiency—It is slightly more efficient than some secondary designs.

The advantages of the secondary method are as follows:

Reliability—Fewer components mean greater reliability. It has greater voltage safety margin on SCRs. It is less susceptible to line voltage transients.

Reversing—It is able to achieve solid-state reversing.

PLATING

Direct Current Plating

Direct current electroplating covers a broad range of processes. These include, but are not limited to, chromium, nickel, copper, zinc, cadmium, silver, and gold. Whereas each of these processes vary somewhat in their particular voltage and current requirements, they all require some form of DC power to deposit the metal out of solution onto the part being plated.

A typical DC plating power supply will have a three-phase input of either 230 or 460 V AC. The output will be somewhere in the range of 6 to 18 V and between 50 and 10,000 A. These values will vary depending on whether still- or barrel-plating methods are employed, the type of finish required, and the size of the parts being plated.

Direct current plating power supplies are relatively straightforward. The incoming AC is converted to DC by means of the main power transformer and either a primary thyristor/secondary diode or secondary thyristor rectification system. In modern systems, the output voltage and current are controlled by the phase angle of the thyristors. Most rectifiers today are equipped with both automatic voltage control (AVC) and automatic current control

(ACC) as standard equipment. In many cases, a variable ramp system is also provided to regulate automatically the rate at which the output is increased from minimum to the desired level.

The ripple component of the output at full-rated power is nominally 5% rms of nameplate rating. This will increase as the thyristor's phase angles are changed to reduce the output. If particular processes demand continuous use of a system phased back, either a properly sized unit should be utilized, or a ripple filter should be installed to bring the ripple component to an acceptable level.

Cooling can be by a number of different methods. Forced air and direct water are the most common. Forced air is acceptable when the surrounding environment is relatively clean and free of contaminants. In a forced-air system, air is drawn in through a series of filtered openings in the rectifier enclosure, forced past the internal power-supply components, and exited through an opening, typically in the top of the supply. Air that contains corrosive materials can cause accelerated deterioration inside the power supply, resulting in reduced life and efficiency.

If a plating rectifier is situated in an aggressive atmosphere, direct water cooling should be considered. Direct water-cooling systems pass water through a series of cooling passages in the main power transformer and semiconductor heat sinks. Water-cooled systems are more compact than air-cooled designs, and multiple rectifier systems can be placed closer to each other than air-cooled power supplies; however, water-cooled systems are sensitive to contamination and minerals in the supply water, and in these cases, the power supplies may require periodic maintenance to clean the water passages and filters.

Pulse Plating

Direct current plating deposits metal utilizing a continuous application of energy, pulse-plating systems provide the opportunity to modulate the voltage or current to achieve different results. The application of gold, silver, and copper with pulse plating results in finer grain structures, higher surface densities, and lower electrical resistance. Additionally, plating times can be reduced by up to 50%. These characteristics make pulse plating attractive, if not mandatory, in the electronics industry.

From an industrial standpoint, pulse plating has found a number of important applications. For example, when used in chromium plating, pulse plating will result in a harder, more wear-resistant surface. In a nickel plating application, using pulse plating may eliminate the need to add organic compounds to control stress and will result in a brighter finish with better thickness control and reduced plating times.

Many plating profiles are available, including standard pulse, superimposed pulse, duplex pulse, pulsed pulse, and pulse on pulse. These waveforms can be obtained from a unipolar power supply. Other variations, possible when using a bipolar pulsing rectifier, include pulse reverse, pulse reverse with off time, pulsed pulse reverse, and pulse-on-pulse reverse. Fig. 3 illustrates a few of the many different pulse waveforms available. The pulsing profile you use will be determined by the type of plating finish desired, the makeup of the plating bath, and the type of power supply available.

There are three basic types of power supply technologies employed to achieve pulsed outputs. The most common design consists of a standard SCR phase-controlled rectifier with a semiconductor switch on the output. Although this system can be successfully employed in almost all pulsing applications, there are some drawbacks, mainly the inherent limitations associated with pulse rise and fall times.

When faster pulsing speeds or square waves are required, linear power supplies are a viable technology. A linear design consists of a fixed output power supply, followed by a parallel combination of field-effect transistor (FET) or bipolar transistors, with the exact configuration determined by the output voltage levels required. This bank of transistors determines the final output by pulsing the fixed DC supplied to it.

The efficiency of a linear supply is generally less than that of a SCR phase-control

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Table I. Pulse Technology Comparison

Type of Power Supply	*Ripple*	*Efficiency*	*Bandwidth*	*Size*	*Cost*
SCR	High	Highest	Low	Mid	Lowest
SCR with filter	Low	High	Lowest	Largest	Low
Linear	Lowest	Lowest	Highest	Largest	Highest
Switcher	Highest	High	Mid	Lowest	Mid
Switcher with filter	Low	High	Mid	Small	Mid

SCR, silicon-controlled rectifier.

ANODIZING

Direct Current Anodizing

As in the case of electroplating, there is a wide variety of anodizing processes currently in use. Electroplating deposits a metal layer onto a substrate, which may be a metal itself or some nonmetallic material such as plastic. Anodizing, on the other hand, is the conversion of the surface layer of a metal to an oxide. The metal most commonly anodized is aluminum, but other metals, such as magnesium and titanium, can also be successfully anodized.

Aluminum will naturally form an oxide layer when exposed to oxygen, but this is a relatively thin layer. Anodizing provides a much thicker coating. Anodized finishes exhibit a number of desirable properties. They are capable of being processed further to modify the appearance of the aluminum. For example, colored finishes are easily obtained by such techniques as dyeing or color anodizing. Anodizing also improves the wearability of aluminum. An anodized finish is much more resistant to abrasion than the base metal. Anodizing is also extensively used in environments where corrosion is a problem.

A number of anodizing processes are employed for aluminum. The most common is the sulfuric acid anodizing process. This provides a coating typically 0.1 to 1.0 mil. thick and lends itself to further color processing. Other conventional aluminum anodizing processes are those utilizing chromic acid (found in marine and aircraft applications) and phosphoric acid (used as a surface preparation for adhesive bonding and as a base for electroplating).

These conventional anodizing processes require a DC power supply similar in nature to those found in electroplating, except that the voltages typically used in conventional anodizing (18–50 V) are higher than those commonly found in plating (6–18 V). Otherwise, the design of the rectifiers for DC electroplating and DC anodizing is basically the same.

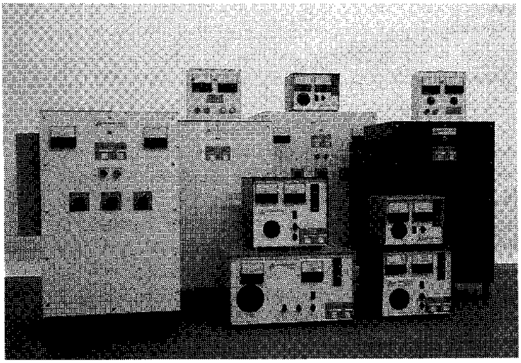
Hard-coat anodizing is often employed in applications where a more abrasive or corrosion-resistant oxide layer than that obtained with conventional anodizing is desired. Hard-coat anodizing processes typically demand voltages between 50 and 150 V, and in many cases, pulse power supplies are utilized to obtain specific results. As in electroplating, the pulse rectifiers are very similar in design, options, and usage.

Color Anodizing

Many architectural aluminum anodizing applications require that color be applied to the finished product. Colored finishes are obtained through the use of dyeing, integral, or electrolytic color processes.

Dyeing is a simple process. A dye bath is composed of water and dyeing material, and the anodized aluminum is placed in the dye bath for some minutes. After removal from the dye bath, the aluminum is then rinsed and sealed in a normal manner.

Integral color is a process by which the color is produced during the conventional anodizing process. Organic acids are added to the anodizing bath, and these acids produce a color, ranging from amber through black, in the aluminum oxide. Standard DC rectifiers are used, though at a voltage approximately three times that found in sulfuric acid anodizing.



The electrolytic or two-step process begins by conventional sulfuric acid anodizing using DC power. The parts are then placed into a coloring solution consisting of salts of various metals such as tin, nickel, and cobalt, and AC power is applied. The AC current causes the deposition of metallic particles in the pores of the anodic coating. By varying the relative amplitudes and times of the positive and negative half cycles of the AC output, numerous colors and finish characteristics can be obtained. The electrolytic coloring processes have become popular as they require less energy than competing methods.

An ideal power supply for the two-step process will provide the opportunity to adjust the voltage and on-and-off times of the positive and negative portions of the output independently. This provides the maximum amount of flexibility to generate the broad range of colors available through electrolytic coloring.

COMPUTERIZATION

In the 1970s many metal finishers investigated modifications that would be required to upgrade their rectifiers to computer control. At that time, however, the price and risk of automation was too high for most companies, forcing them to continue using manual control.

Today, the importance of incorporating some degree of automation into the metal-finishing processes is becoming more evident. For example, smaller firms find themselves at a disadvantage when competing against larger, more automated companies, especially for jobs where the finished parts require precise coating thickness and consistent finish qualities. Additionally, certain plating applications require multiple layer applications to achieve the desired coating thickness and surface quality. These multilayer processes demand extremely accurate and repeatable coatings.

The major advantage of computer over manual control of a rectifier is the computer's ability to repeat a particular operation or procedure time after time. Computers can perform a variety of different functions when integrated with rectifiers. The computer can simultaneously monitor a number of output currents and voltages, detailing them on a video-display terminal. It can also maintain those voltages and currents within designated parameters, thereby compensating for varying input voltage or load changes. The computer can easily regulate pulsing and reversing power supplies. The computer replaces the switches, meters, and potentiometers typically required for manual operation; yet a manual override is included in case of malfunction.

The advantages of a simple computer package are easily seen. The first major improvement is in the consistency of a finished product. Due to the precise application of power, the coating is exact from piece to piece, and this can significantly reduce rework and reject rates. Furthermore, a computer's precision control of cycle times and rectifier operation can reduce power consumption, resulting in lower electricity bills. Finally, the computer can calculate and transfer exact amounts of chemicals to finishing tanks, minimizing associated material costs and reducing waste and sludge-disposal expenditures.

A computerized system should be custom designed for the specific application, regardless of the size of the finishing operation or the degree of automation desired. Customization is the key to successful systems integration. The system should, however, be designed and constructed using standard components. This procedure provides a system that exactly matches the needs of the user while minimizing the initial cost.

A computer control system typically consists of a number of basic component groups. The illustration in Fig. 4 shows the structure of a multiple rectifier computer control system. A review of each of the basic groups provides a better understanding of how the system works as a whole.

The Rectifier

For a rectifier to be controlled by a computer, there must be a means for the computer to communicate with the rectifier. The rectifier must then be capable of modifying its

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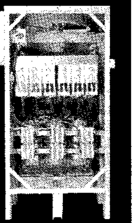

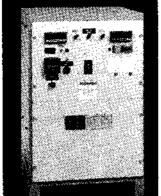

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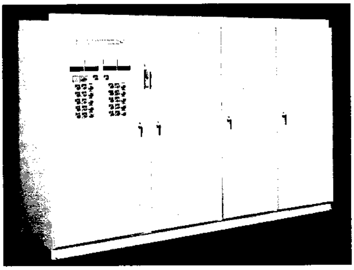

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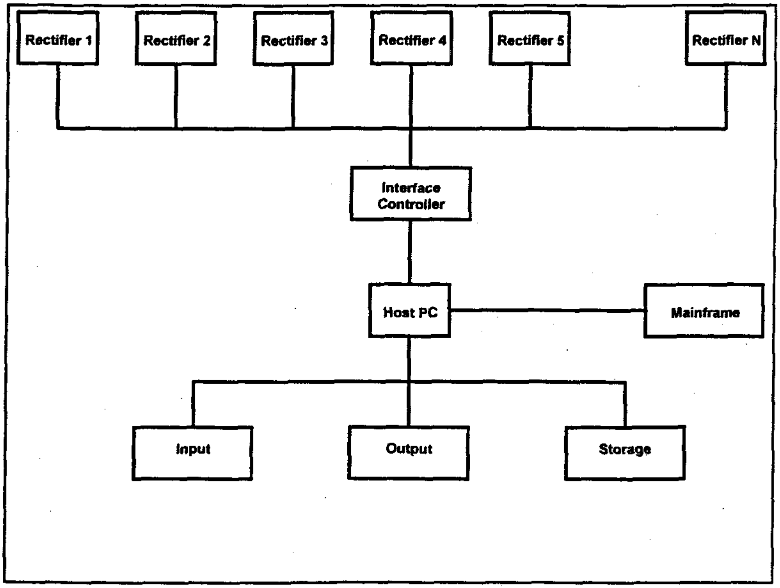


Fig. 4. Multirectifier computer-controlled system.

operation to satisfy the requests of the computer. Typical commands sent from the computer to the rectifier include output voltage, output current, ramp timer, ramp rate, power on/off, and cycle start/stop.

Additionally, information might be sent from the rectifier to the computer, for example, power status, output voltage, output current, interlock status, and cooling system operation.

In some instances these signals will be transferred directly between the computer and the rectifier. In other cases there may be an intermediary computer that processes some or all of the information. A third situation may arise in which there is a single board computer located in the rectifier itself that has the singular role of operating the rectifier based on data from the control computer. Virtually any rectifier utilizing solid-state electronics to control the output can be adapted to computer automation.

The Host Personal Computer

The host personal computer (PC) is the center of the automated system. It is typically configured around a PC compatible and can be enhanced by a wide variety of peripherals. The host computer is the "brains" of the system, providing the input/output, storage, and communications capabilities needed for optimum operation.

Input Devices

In most cases a keyboard is used to enter information into the computer. It allows an operator to change process data, load parameter profiles, or commence or terminate plating cycles, along with other functions determined by the user.

Most host PCs will include a floppy disk drive. Floppy disks may contain data such as profile information, system software updates, and security codes. The floppy disk can be programmed by a supervisor on a PC in his/her office, and the disk can then be taken to the host PC and the data transferred.

Another type of input device is a bar-code reader. A bar code consists of a series of alternating black and white vertical bars that contain information defined by the user. A bar-code scanner is passed across the bar code to read it. The spacing and width of the bars determine the data contained therein. Information such as part number, process identification, vendor, and customer are typical examples of data that can be contained in a bar-code format.

Output Devices

A monitor to verify data being entered from one of the input devices is necessary with any computerized system. Once a process is running, the monitor can display a number of different screens. These screens can include process status, alarm conditions, rectifier operation, and virtually any other information desired by the user. It is quite possible for the computer to monitor, display, and control nonrectifier operations, such as bath heaters/coolers, bath agitators, and chemical feeders.

A printer may be desired to obtain a hard copy of any of the data recorded or operations performed by the computer. This information can be used in a number of different ways, from statistical process control to process tracking.

Data Storage

A means to store the operating system, control programming, process profiles, and operating data must be provided. The most economical data storage device is a hard disk, which should be located in the host computer. By using a hard disk a process profile can be retrieved almost instantaneously simply by calling up a code number or name. By using profiles from the computer to control the metal-finishing operation, as opposed to setting parameters manually by turning knobs and pushing buttons, consistency is maintained.

Some method of backing up the data on the hard disk is mandatory. If, for example, there is a power disruption or a failure of the computer, information will most likely be lost. If a regular backup is performed many hours of reprogramming may be avoided by simply restoring the data from the backup device to the computer. Although floppy disks are commonly used for backup, a streaming tape system, which utilizes a removable tape cassette, is a much better alternative, as all the data from a hard disk can usually be stored on one tape.

The Interface Controller

The interface controller acts as the translator between the computer and the rectifier. It receives commands from the computer and converts those commands to a language the rectifier can understand. The rectifier transmits information to the interface controller, which sends it to the computer. Both inputs to, and outputs from, the interface controller come in digital signals over interface cables. The interface controller may be situated in the computer itself, or it may be a separate system located adjacent to the computer.

The Interface

To keep the equipment as standard as possible, the popular choices for interfaces are the RS-232 and RS-422. Each requires only a pair of shielded, twisted wires to transmit information. This significantly reduces the number of wires needed for a multiple-rectifier system, as the twisted pair simply connects from the interface controller to each rectifier in a sequential fashion. In other words, the same pair of wires goes to the first rectifier to the second to the third, and so on. This eliminates the many wires that are commonly found connecting remotely located control panels to rectifiers.

The Software

The software should consist of standard control packages modified to meet the user's specific requirements. A language such as Quick Basic, used on the host computer, will provide the necessary operating speed for the host, along with the ability to modify or upgrade the program easily at any point. Faster languages, such as assembly code, may be required for a microcomputer located on the rectifier to control output waveforms adequately.

A Main Frame

A link between a main frame and the host computer is always a possibility, increasing the overall capability of the system. Such a link might be the first step toward complete factory automation. Use of a main frame provides a means for data from all parts of the finishing operation to be accumulated, correlated, and disseminated to various departments.

For many smaller and middle-sized operations, computer automation is becoming financially feasible. Benefits include reductions in rework and reject rates, in downtime, and in chemical costs. Additional savings could be realized by the reduced power usage of a computer-controlled operation. In the near future computer automation may very well be the key factor in whether certain metal-finishing operations are profitable.

RECOMMENDED TEST EQUIPMENT

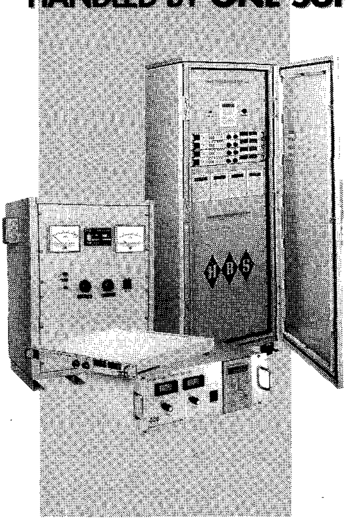
Aside from the usual hand tools usually found in a well-equipped industrial tool box, the following are recommended tools for power supply troubleshooting:

1. A clamp-on AC ammeter
2. A digital volt-ohm meter (DVM)
3. A battery-operated oscilloscope

There are several options to consider when purchasing these instruments for testing in an industrial environment. The clamp-on ammeter should be an AC device, as it will be used at currents up to 1,000 A AC. All exposed metal parts must be sufficiently insulated to ensure safe use around 600 V AC equipment. An analog-type clamp-on ammeter is preferred over most digital ammeter types, unless the digital unit is sufficiently filtered to prevent display jitter when measuring incoming line AC. When buying a digital ammeter, one should test the instrument on an operating power supply before making the final purchase decision.

The digital volt-ohm meter best suited for power-supply testing is battery operated and durably packaged so that it will stand up in an industrial environment. A heavy-duty rubber-covered case is best. To be the most useful, the DVM should have "true rms reading" capabilities. Make sure that the test leads are equipped with heavy plastic leads and rated for 5,000 V DC service. The DVM should have at least the following ranges: voltage of 10 mV to 1,000 V AC and DC, current of 1 to 10 mA AC and DC, and resistance of 0.1 ohm to 10 megohm. Some additional features to look for are autoranging and/or a diode testing range, which measures the forward voltage of a diode rectifier. An alarm on some DVM instruments is a convenient means to measure continuity in cables and wire harnesses.

The oscilloscope should be a high-quality, battery-operated portable instrument. Some models incorporate a built-in digital display, which allows one to observe the power-supply output waveform while reading the DC operating point and the AC ripple content at the output bus. Although an oscilloscope is not always necessary, you will find it a convenient tool when making a quick check on an operating power supply to see if any further testing is necessary.



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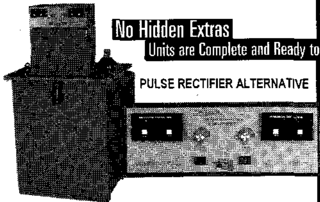

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Of these three electronic tools, the clamp-on ammeter is the first one you will most likely use to measure the three-phase line current. The measurement point should be just after the main contactor, near the transformer input terminals. This measurement can be performed at no load to determine the magnetizing current of the main transformer, which should be about 5% of full load rated line current. With a load on the DC output bus of the rectifier, the balance of the AC line current can be measured, and the three line currents should be within 10% of each other.

The next instrument you may use is the DVM. It will allow you to verify the three-phase, line-to-line input voltages at the thyristor regulator section just ahead of the main transformer. If you then measure the line-to-line voltages on the transformer side of the thyristors, you can determine if the thyristor regulator part of the system is feeding balanced voltages to the main transformer.

The oscilloscope is valuable when performing fast maintenance checks on a number of power supplies. The scope should be connected to the back of the output DC panel voltmeter. As the voltage control on the panel is increased, a waveform will appear that has six peaks and valleys for each cycle of the line frequency. Each period is 16.6 milliseconds long. If any of the six major peaks is missing or the valleys are too wide, there is a serious problem in the power circuit that must be investigated further.

BASIC TROUBLESHOOTING

This section briefly describes some basic diagnostics to determine why a power supply is not operating properly. Before starting any diagnostic test on a power supply, you should obtain a copy of the electrical schematic drawings for the particular equipment you are working on. On these drawings, you should be able to identify the basic functional areas that make up virtually any rectifier. The four basic building blocks of a power supply are the following:

1. Electrical controls
2. AC power circuits
3. DC power circuits
4. Electronic controls

CAUTION: Only qualified personnel should attempt to service power supply equipment. Dangerous and lethal voltages may be present.

The electrical controls provide simple low-power functions for the power supply. You will notice such items as push buttons (stop, start), pilot lights, relays, timers, limit switches, flow switches, thermal switches, thermal overlay relays (heaters), and other 120 V AC protective devices. These items are typically drawn in the familiar ladder diagram format. Diagnostics in this area will usually require the DVM to measure continuity or the presence of control voltages at various components.

To check for proper voltages at the low-power components, find the common on the ladder diagram and attach the voltmeter to it in the actual circuit. With the control power energized, you will be able to check the AC controls on the ladder diagram and measure for the presence of an AC voltage at the corresponding point in the actual circuit. This method is most useful when there is a loss of control circuit voltage that prevents a portion of the controls from working properly. When the missing voltage returns at a particular point in the circuit, this indicates you have just moved past the defective component, such as a contact, a terminal, an interlock, or a thermal switch. The faulty component can then be repaired or replaced. You may find there is more than one bad part; so be sure to test all of the low-power components.

The AC power circuit is the portion of the power supply located between the AC input power terminals and the regulation thyristors at the primary of the three-phase power transformer (assuming a primary thyristor/secondary diode configuration). The components representing this AC power section are usually found near the center of the electrical schematic.

The clamp-on ammeter is the diagnostic tool used in the AC power circuit. Place the ammeter around one of the incoming AC conductors. Operate the power supply with no load and check that the magnetizing current of the main transformer is no more than 5% of the full load rated line current, which is usually indicated on the electrical schematic. If this reading is correct, the next step is to measure the line current with a load of parts in the process tank that will require full output of the power supply. Measure all three incoming lines and verify that the currents are balanced to within 10% from one phase to the next. If an imbalance is detected, there could be a fuse blown or a thyristor shorted, or the gate signal to some of the thyristors may be improper.

To determine which of the above is the problem, use the DVM on a high AC voltage range and measure the line-to-line AC voltages. Extreme care should be exercised when making line voltage measurements to prevent any metal parts from coming in contact with the live conductors. At the same time, protective eye wear should be used. Measure the line-to-line voltages at each of the thyristors, after the thyristor fuses. If all voltages are okay, no fuses are blown, and all contactors and safety switches are working, next measure the line-to-line voltage at the output of the thyristors near the connection to the primary of the main power transformer. If these voltages are relatively balanced but reduced in value, the thyristor regulator is in proper working condition.

If after testing both the electrical controls and the AC power sections you find that everything is normal (i.e., no defective fuses or thyristors, all electrical controls functioning) except for unbalanced line currents, there may be a problem with the main power transformer or the diode section on the low-voltage secondary side of the transformer.

The DC power section typically consists of diodes, output bus connections, and metering for output voltage and current (in a secondary thyristor configuration, you would find thyristors in place of diodes). Testing in this section of the power supply consists of locating shorted or open diodes and verifying metering calibrations. Because of the high currents that flow in the low-voltage diode busing, a loose connection will cause a great deal of heat to be generated, which will cause a discoloration of the copper bus bars. By physically inspecting the DC power section in detail, some of these connection problems may be located and repaired simply by cleaning. The clamp-on ammeter may be useful for moderate-sized diodes that are supplied with a flexible cable connection from one side of the case.

Diodes that are supplied with a flexible connection at one end of the case can be checked with the clamp-on ammeter. Measure the current at each diode by placing the clamp-on ammeter around the flexible lead. A diode that is open will draw no current, whereas a diode that is shorted will draw excessive current. In either case, the diode should be replaced. As these diodes are removed, the DVM may be used on the diode range to verify that the diode being removed is, in fact, bad. A defective diode will read either open or shorted in both directions.

The DVM may be also used to determine possible metering circuit defects. To check the power-supply voltmeter, measure the voltage across the output terminals of the rectifier and the terminals at the back of the panel voltmeter. Compare these readings with that of the panel voltmeter. They should all agree.

Current is typically determined by measuring the voltage drop across a precision resistor placed at the output terminals known as a shunt. This voltage drop at full output will typically be 50 mV. This low-level voltage signal has to be multiplied by a factor before comparing it to the actual meter reading.

The oscilloscope is useful in locating problems where complete diode circuit branches have burned open and left a missing section in the wave shape; however, this may also be a symptom of thyristor problems on the primary of the main transformer. If the AC ripple component of the output is important to the process, then an oscilloscope with a built-in true rms feature can be used to view the ripple waveform, as well as determine the AC to DC ratio of the ripple using the AC and DC coupling of the scope.

The electronics are the most complex part of the power supply. Electronic circuits are usually indicated on schematics by boxes with terminal numbers and functions labeled along the edges. The DVM is commonly used in the testing of these electronic circuits to measure signal and control voltages. Although there are many different types of electronic circuits, two are found in every power supply and must function correctly for proper power supply operation. These are the drive circuit and the firing circuit. In some cases, these will be on one circuit board, whereas at other times, they will be on separate boards.

The drive circuit is an analog amplifier circuit. It receives current and voltage reference signals from the operators ACC and AVC potentiometers. These control signals will typically range between 0 and 2.5 V DC, depending on the position of the operator controls. To check a typical drive circuit initially, verify that there is 120 V AC on the power terminals and that there are reference voltages on the ACC and AVC input terminals. You should then have a voltage at the output terminals. If no signal is available at these output terminals, the drive circuit may be defective or seriously out of adjustment. Remove and further test the drive circuit using the test procedures found in your operators manual.

The firing circuit accepts the output signals of the drive circuit and produces synchronized gate pulses that fire the thyristors in the AC power circuit, which in turn regulates the voltage to the primary of the main power transformer. To test this circuit, ensure there is a signal of more than 2V DC at the input from the firing circuit. Then measure the signals at the gate outputs to the thyristors with the DVM. They should typically be about 1 V DC. Perform these measurements with great care against shorting any of the leads to ground or to another pair of terminals, as there may be line voltages of up to 600 V AC between these terminals and ground. As with the drive circuit, if any signals are missing or incorrect, remove the board and bench repair using the procedures outlined in the operators handbook.

BASIC REPAIRS

Once a defective component has been located, it should be replaced with a part of comparable quality and ratings. It is especially important when replacing temperature sensors that the replacement have the same temperature rating as the original.

Caution: Before attempting replacement of any component, ensure that the power is removed from the rectifier and that the capacitors are discharged.

Electrical and Electronics Components

Replacement of electrical components, such as push buttons, thermal switches, relays, and switches, as well as electronic PC boards, is relatively straightforward. Carefully mark all connections to the defective device before removal, replace with the correct item, and reattach the wires. It is also advisable to check the rest of the rectifier for clean and correct connections at this time.

Thyristors and Diodes

Thyristors are typically found in modular, stud-mount, and flat-pack configurations, whereas diodes are usually the stud-mount or flat-pack style. The replacement procedures for stud-mount and flat-pack thyristors and diodes are virtually identical, with the difference being that thyristors will have two additional small leads to be attached.

The modular thyristor is the smallest of the three types and is typically found in lower power systems. The module contains two thyristors and has terminals for connecting gate and input/output leads. Mounting holes in the base allow attachment to the bus bar. To replace a modular thyristor, perform the following steps:

1. Note where the gate and input/output leads are attached.
2. Mark the leads and remove the thyristor.
3. Clean the bus bar surface and the new thyristor surface.
4. Apply heat sink compound sparingly to both surfaces.
5. Fasten the new thyristor to the bus bar.
6. Reattach the leads. Replacement is now complete.

Stud-mount thyristors and diodes are no more difficult to replace. Stud-mount devices can be mounted on either air- or water-cooled heat sinks and are typically found with ½ or ¾ in. diameter studs. Replacement of stud-mount devices is the same for both air- and water-cooled systems, following the steps below:

1. Mark and remove the two signal leads from the terminal blocks (thyristor). One of these is the gate lead, and the other is the cathode signal lead.
2. Remove the large braided cable.
3. Remove the nut and washers, and remove the device from the heat sink.
4. Clean the bus bar and new thyristor surfaces.
5. Spread a small amount of thermal compound on the new thyristor, taking care not to get any compound on the thyristor threads.
6. Insert the stud in the heat sink, reassemble the flat washer and the star washer, and then tighten the retaining nut.
7. Attach all leads to the proper locations, being sure that all connections are clean and tight.

Flat-pack thyristors and diodes, sometimes referred to as "hockey pucks," are used in higher power rectifiers. They range from 2 through 4 in. in diameter. As with the stud-mount devices, the only difference between a flat-pack thyristor and diode is the presence of gate and cathode leads on the device.

A flat-pack device is secured between two current-carrying bus bars by a clamping mechanism. Some clamps have indicators built in, whereas others do not. When replacing a device secured with a gauged clamp, note the reading before removing the device.

The other type of clamps used are either 5,000- or 10,000-lb clamps. These systems consist of a pair of clamping bars, connected by two studs, between which is sandwiched the bus bars, a Belville washer system, and the semiconductor device. Replacement of thyristors or diodes utilizing these types of clamps requires the use of measuring devices. The following steps should be taken to replace a flat-pack thyristor or diode (refer to Fig. 8).

1. Note the clamping arrangement being used. If a gauge is present on the lamp, record the indication. Mark and remove the gauge and cathode leads if replacing a thyristor.
2. Uniformly and slowly loosen the nuts on the clamp studs. Remove the Belville washer assembly and the device. Note that the Belville washer is made up of four parts: a centering section, a flat washer, and two concave washers.
3. Clean the surfaces of both bus bars and the new thyristor or diode. Clean both clamping bars, and check that the insulated surfaces of the clamp have not been damaged.
4. Apply heat sink compound sparingly to both surfaces of the device and to the bus bars.
5. Place the new flat pack in the clamping mechanism, ensuring that the device is oriented properly. Check the other devices to verify this. There are typically roll pins in the bus bars that align with depressions in the device. Make sure the roll pins do not damage the flat-pack surfaces.
6. Reassemble the Belville washers as shown, making sure the two concave washers are back to back. Now place the washers in the clamp.
7. Finger tighten the clamp nuts, ensuring all parts are situated properly, and tighten the nuts with a wrench one-quarter additional turn. Check that approximately the same number of threads are visible beyond the nuts on each stud.

8. Using a depth gauge, measure through the center of the hole in the bus bar and Belville washer system. Note this reading.
9. Tighten each nut one-half turn, and recheck with the depth gauge. Continue this tightening procedure until the difference from the original reading is 0.048 ± 0.004 in. for a 10,000 lb clamp, and 0.026 ± 0.002 in. for a 5,000 lb clamp.
10. Reattach the gate and cathode thyristor leads.

PREVENTIVE MAINTENANCE

Nothing is more important to rectifier reliability and longevity than a consistent program of preventive maintenance. The efforts expended in taking periodic care of any equipment, especially those operated in the aggressive environments typically found in metal-finishing processes, will be returned many times over.

The following provides a brief outline of the minimum maintenance that should be performed every month and every 6 months. The program you implement should take into consideration the number of rectifiers, how many shifts, what type of processes, and the duty cycles of your particular operation.

Monthly

1. Ensure that all doors and panels are on the rectifiers and that the area around the rectifier is free and clear of items that would hinder proper airflow or operation.
2. On air-cooled systems, wash or replace the air filters. Refrain from using inexpensive cardboard framed filters, as the thin metal facing can quickly deteriorate and be drawn into the rectifier. Also, check that the fan blades are secured to the fan motor shafts and that they run without vibration.
3. On water-cooled systems, remove and clean or replace the inlet water strainer. Check all water lines for signs of leaks or contamination accumulations. If contamination is evident, determine the source and correct if possible.
4. Check panel gaskets and repair or replace as necessary.
5. Check components such as pilot lights, switches, push buttons, etc., for proper operation and replace as required.

Every 6 Months

1. Check writing and bus connections for tightness and cleanliness. Repair as required.
2. Clean semiconductors and heat sinks. Dirty and corroded heat sinks can significantly increase the operating temperatures of the semiconductors and reduce the life of the rectifier.

FUNDAMENTALS OF PLATING RACK DESIGN

by Steen Heimke

Belke Mfg. Co., Chicago

The primary purpose of a plating rack is to hold a part in the most advantageous position for exposure to a plating current, which flows from an anode. Plating provides protective finishes to parts fabricated prior to plating so that the metal finish will not be damaged or ruptured during the fabrication process. Parts requiring a finish have an infinite variety of shapes and sizes, resulting in the need for fabrication of a custom plating rack. Before a plating rack can be fabricated, certain questions must be asked.

What kind of plating will be done?
What solutions will the rack be exposed to?
What rate of production is necessary to be cost effective?
Will the tips be stripped with a proprietary solution?
What portion of the part is to be plated?
How should the piece be held for proper density of the plating finish?
What sort of tip must be designed for proper positioning?
Will this design provide quick and easy racking and unracking?

For determining the answers to some of these questions, the basis for a good rack design will be developed. Proper rack design should be started with a description of the part, detailing any special surface problems, shading, and contact tip marking. Where can the piece be held? The number of pieces per rack will be determined by current per rack, weight of each part relating to total weight of the rack, and, most importantly, by the design of the rack.

RACK DIMENSIONS

The most important fundamental of plating rack design is determining the proper dimensions, making sure that each rack will fit with parts affixed into the smallest process tank in the plating line.

Dimension A—Overall Length

This is the distance from the cathode bar to the bottom of the rack, keeping in mind that each process tank has different space requirements relating to anodes, steam coils or immersion heaters, air agitation pipes, filters, overflow dams, and mechanical agitation. The rack should be several inches off the bottom of the tank, allowing for some accumulation of sludge. Also, improper anode length could result in a very uneven deposit.

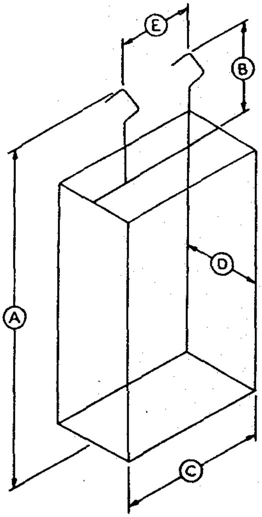
Most parts should be positioned a minimum of 2 in. under the solution surface. It is important to check solution levels in all process tanks. Determine the dimension from the lowest level tank, thereby assuring complete immersion throughout the plating cycle.

Overall length is determined by Figure 1, dimension A, which is the distance between the cathode hook and the bottom of the rack.

Dimension B—Distance from Cathode Hook to Location of First Part

This dimension is very critical as it will determine the number of parts per rack.

Fig. 1. Rack dimensions



Dimension C—Width

On return-type automatics, this width dimension is the direction of travel. Proper dimensions are extremely critical, as each manufacturer may have different width requirements. As in any automated system, this dimension might have some variables and the rack must be designed for the smallest cell. Improper width could result in damaged racks because of machine jam-ups.

This dimension on automated hoist lines or manual straight lines determines the number of racks on each work bar. Spacing between the racks is important, as this will ultimately determine production rates. How many racks will effectively fit on a work bar? Look at the design of the work bar to help with proper spacing, especially the location of the pick-up points.

Dimension D—Thickness

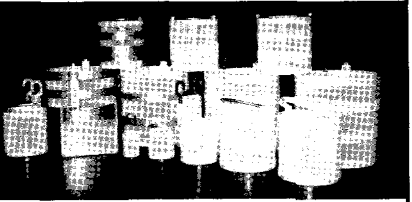
The thickness dimension is the direction of travel on an automated hoist line. Relating to plating rack design, this dimension is the most critical. The distance between the anodes and their relationship to the cathode bar will determine how wide the rack will be. The rack must fit between the anodes with ample room for holding the parts (usually 1–3 in.).

On a manual line it will be necessary to determine the smallest anode distance so that the rack will fit in all process tanks. Another factor on a hand line is making sure that the plater can easily put the rack in and out of each process tank without knocking parts off.

Dimension E

This is only for racks that have a double cathode hook and is usually for return-type automatics. This design is also used where additional stability is required or where weight might be a factor.

Having developed all the dimensions necessary for design of the spine, special attention must be focused on cathode hook design. What size of work bar will be used? It is important that the hook make clean contact with the bar so that current flows properly. This can be



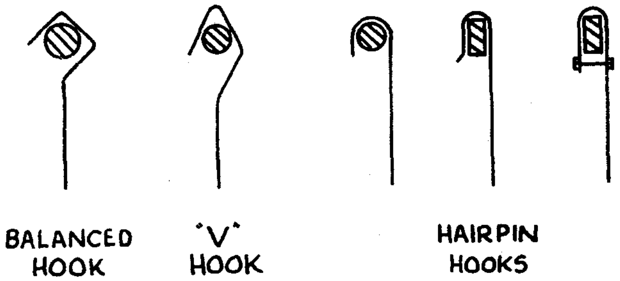


Fig. 2. Hook shapes.

accomplished with the V-hook design, the most commonly used today. (See Fig. 2 for commonly used hook shapes.) Some manufacturers have developed their own hook design. Recent work bars have been rectangular for the primary reasons of stability in relationship to the speed of the machine and quick starts and stops.

CONSTRUCTION OF THE PLATING RACK SPINE

The plating rack spine (Fig. 3) is the backbone of a rack. It must be capable of carrying the necessary current to each tip, it must have adequate strength to support all the parts, plus be wear resistant, especially for use on an automatic machine. The plating bath in which the rack will be used has a known current density rating in A/ft^2. Multiply this factor by square feet of parts on the rack to determine how much current the rack spine and hook must carry. (See Table I for plating solutions—cathode current densities.)

Generally, most single spines are fabricated with ¼ × ¾ in. or ¼ × 1 in. copper, which will carry 200–250 A. (See Table II for a chart of relative conductivity.) Copper is the most commonly used material, as it has the highest conductivity in relationship to price.

Sometimes cathode hooks fabricated of copper and spines fabricated of steel, stainless steel, brass, or aluminum can be used if the connection is below solution level. Again, the main factor is conductivity. Steel, stainless steel, brass, and aluminum have lower conductivity than copper. The most common practice is to use steel for supporting members and not where conductivity is needed.

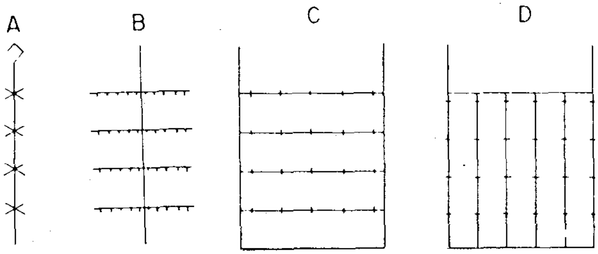


Fig. 3. Four basic types of plating rack construction; A — single spine; B — T type; C — box type; D — multiple spine.

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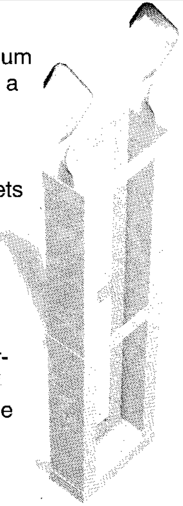

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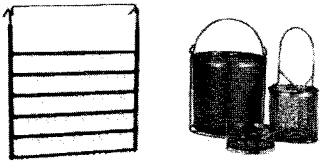

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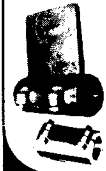

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Table I. Plating Solutions—Cathode Current Densities

Plating Bath	*A/ft^2*	*Voltage*
Brass	5–20	2–5
Cadmium	5–50	2–5
Chromium (decorative)	100–200	4–6
Chromium (hard)	200–500	5–12
Copper (sulfate)	15–50	1–4
Copper (fluoborate)	15–50	1–4
Copper (cyanide)	20–60	2–5
Gold (acid)	10–30	5–6
Nickel	20–100	4–8
Silver	5–30	0.5–2
Tin (fluoborate)	25–150	1–3
Tin (stannate)	30–100	4–6
Tin (sulfate)	10–40	1–4
Zinc (cyanide)	10–90	1.5–6
Zinc (low cyanide)	20–80	1.5–6
Zinc (acid noncyanide)	20–80	1.5–6

DESIGN OF PLATING RACK TIPS

Some practical objectives in the design of the tip are easy racking and unracking; adequate current flow (contact) to the part; tip designed to hold part in noncritical area; type of tip—gravity or spring type; and material.

Gravity Tip

A gravity tip is one that is styled for easy racking and unracking. The part to be plated usually has a hole for the tip to fit through. This style is most commonly used in zinc, electroless nickel, cadmium, or silver baths.

Spring-Type Tension Tip

A spring tension tip is used in baths, which require greater throwing power and positive contact such as chromium plating or anodizing. They are also needed whenever mechanical or air agitation is used.

Table II. Chart of Relative Conductivity

Size (in.)	*Copper*	*Aluminum*	*Brass*	*Steel*	*Phosphor Bronze*	*Stainless Steel (300 series)*	*Titanium*
1 × 1	1000	600	250	120	180	23	31
¾ × 1	750	450	185	90	135	17	23
½ × 1	500	300	125	60	90	12	16
¼ × 1	250	150	63	30	45	6	8
1 (dia.)	785	470	196	94	141	18	24
¾	445	265	111	53	80	10	14
½	200	120	50	24	36	5	6
¼	50	30	13	6	9	1	1½
3/16	28	16	7	3½	5	⅝	⅞
5/32	20	12	5	2½	3⅝	½	⅝
⅛	12	6	3	1½	2	¼	⅜
3/32	7	4	1¾	1⅞	1¼	3/16	¼
1/16	3	1¾	¾	½	½	1/16	3/32

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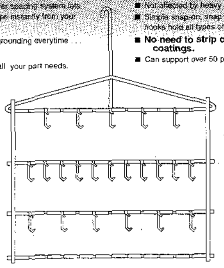

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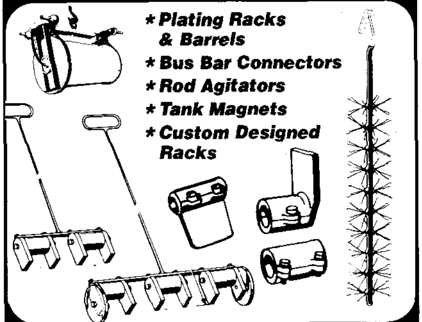

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Some principles of plating must be remembered in designing a plating tip. Areas around the edge of large flat surfaces tend to plate more heavily than the center section. Edges will be exposed to higher current density. Parts with sharp points might require special care to prevent burning.

In some cases, auxiliary anodes are needed so that the plating deposit remains consistent and uniform within the plating specifications. Auxiliary anodes can reduce plating time by throwing a deposit into hard-to-reach areas requiring less plating time. Whenever an auxiliary anode is needed, special care should be taken in construction to make sure that it does not come in contact with the cathodic section of the rack. A nonconductive material is used to separate the anode and cathode sections. The material most commonly used is a fluorocarbon plastic because it can withstand the curing process. Polypropylene blocks can be used and added as a finishing operation.

Design of the Spring Tension Tip

Questions to be considered in the design of a spring tension tip are:

What area of the part is most critical in the plating bath?
Where can a rack tip mark be permitted, as it is almost always present?
Of what kind of material is the tip fabricated?

Referring to the critical area to be plated, thought must be given to the part location relative to anode configuration, drainage of the part, high and low current density areas, and gassing around holes and openings.

A part should be held so that the rack mark is in the least critical area. Thought should be given as to what the end result will be with the finished plated part assembled and complete. After looking at this, a more objective rack mark area can be determined.

Special care must be taken to make sure that the contact is secure, will hold the part throughout the plating cycle, and will not scratch the part.

Materials Used for Tips

The two most common materials used in the fabrication of plating rack tips are phosphorus bronze and stainless steel in both gravity- and spring-type tips. Other metals commonly used with a gravity tip are Monel and titanium.

In the case of materials used for a spring-type tip, spring tempered or half-hard material is needed either in flat or round stock. Spring tempered is preferred because of the spring action present in the material, reducing metal fatigue. In the fabrication process sharp bends should be avoided as they create a fatigue factor and eventually the tip will break. In recent years, stainless steel has been widely used as a tip material because of the use of proprietary nitric or muriatic acid stripping solutions. Using phosphorus bronze with such strips would cause the tip to dissolve prematurely. It must be stated that phosphorus bronze has a greater current carrying capacity and should be used where current is a factor. Stainless steel tips do create some problems as their conductivity is so low that excess heat is created and could cause a premature breakdown of the plastisol rack coating.

Large parts are generally fabricated using flat stock, whereas smaller parts can use round stock.

FIXED VERSUS REPLACEABLE TIPS

There are two types of racks used in plating: fixed tip and replaceable tip. Each style has its own advantages. Fixed tip racks are generally less expensive on the original outlay, and usually require a very tough tip because of the weight of the part and/or rack.

The replaceable rack tip concept offers some advantages over a fixed tip rack:

1. Plating racks can be maintained at 100% capacity. When analyzing how many parts can be put on a rack and knowing what it takes to operate a plating line at a profit, each tip becomes a profit center with this concept. Whenever a tip breaks it can be replaced, thereby creating a consistent production output.

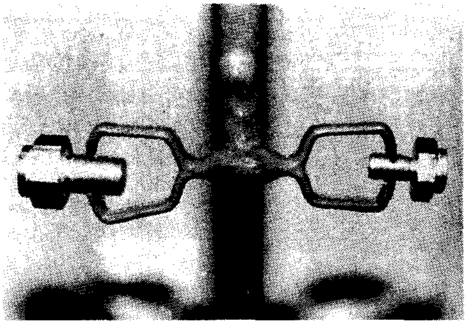


Fig. 4. Double tip connection.

2. The replaceable tip allows many different and varied styles of tips to be used with the same spines, reducing the need to inventory racks for every style of part.

3. Cross bars can be made replaceable instead of every tip, creating some additional cost effectiveness.

4. The repair of the complete rack would be unnecessary as only the tips have to be replaced.

Connecting the Tips to the Spine

The most common method of attaching the tip to a spine is with a mechanical connection using a machine screw, lock washer, and nut. Materials vary with each manufacturer, but usually stainless steel, steel, or brass are used. Stainless steel connections are desirable because in the event of rack repair they suffer less corrosion attack than steel.

Using copper or steel rivets is faster in assembling, but creates a problem when the rack has to be repaired and tips moved.

To connect a tip to a spine, a hole is drilled in the spine that will allow the screw to fit through, with a nut to attach to the screw for secure fastening. Using this type of connection, it might be desirable to solder the tip to maintain strength and corrosion resistance.

To maintain corrosion resistance, tip connections should be lead soldered. Silver solder can be used to increase conductivity in tip construction, but will increase the cost.

Most tips can be affixed to the spine with a single mechanical connection, but with large parts a double connection should be used. A double connection (Fig. 4) is desirable whenever the racking or unracking gives the operator an opportunity to give the tip a certain amount of torque by constant twisting, pulling, and adjusting, thereby loosening the connection at the spine. A double connection minimizes the chance of this happening.

Types of Replaceable Tip Connections

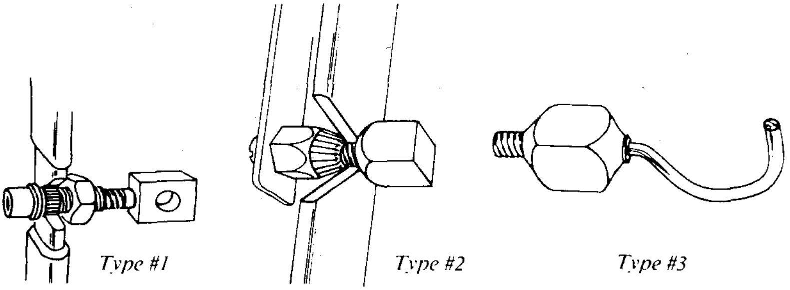
Type #1: This replaceable tip (Fig. 5) has a knurler, which bites into the copper spine with a stainless steel stud drawn tight with a plastic cap. This type of tip is normally lead soldered for corrosion resistance and strength.

Type #2: This replaceable tip uses a knurled section and threaded stud, which is drawn through a hole and then locked in place with a cap nut.

Type #3: This type represents a gravity-type replaceable tip either plain or plastic covered. This unit is threaded directly into the spine or cross bar.

COATING OF RACKS AND SPINES

The final process in fabricating a plating rack is the coating. This coating is commonly called plastisol or PVC (polyvinyl chloride) resin. Plastisol is 100% solid material and


Type #1

Type #2

Type #3

Fig. 5. Various types of replaceable tips.

contains no solvents. Plastisol must be heated and cured at a temperature of 375–400°F. Prior to coating, the racks or tips are primed with an adhesive cement, which helps the plastisol adhere to the racks.

In the curing process, it is important that the oven maintain a consistent temperature for an even cure. The oven is vented to remove any curing smoke and plasticizers. Even before the rack or tip is cemented, it is necessary to rough up the surface for adequate adhesion. This process is called blasting—normally a procedure using some abrasive-type media such as aluminum grit, sand, or metal shot.

The plastisol's primary function is to provide a corrosion protective coating, which is impervious to the acid or alkali attack that is prevalent in every plating line. Plastisol racks and tips can be trimmed easily, exposing only the contact area to grip the part to be plated.

Large racks will pick up more plastisol than small ones. It is important to try to maintain a consistent thickness, keeping in mind that small wire tips will retain very little heat and, therefore, pick up a lesser amount of coating. Replaceable tips have some advantage by being coated separately and retaining more heat, developing a thicker coating.

When plastisol is exposed to a trichloroethylene or perchloroethylene solvent, it will leach out the plasticizer and cause the coating to harden and crack.

SPECIAL APPLICATIONS

Anodizing Racks

Anodizing racks are presently constructed out of two kinds of materials: aluminum or titanium. Generally, anodizing racks are not coated. The main factor, as with copper racks, is that the contact with the anodized part must be positive. Titanium and aluminum do not lend themselves to spring-type tips as they are not spring-tempered materials. Aluminum is a much cheaper material, but it will be chemically attacked and also requires stripping of the anodic film after each cycle. Titanium has excellent corrosion resistance, long life, and maintenance-free operation. Titanium racks can be completely assembled with titanium nuts, bolts, and screws.

Printed Circuit Board Plating Racks

The requirements for printed circuit board (PCB) rack design for electronic plating of all types and sizes of boards are as complex as the microchip itself. The PCB rack must be designed to hold the board in a locked position with positive contact on the border of the board (see Fig. 6). The board must be held securely because of mechanical or air agitation in the various baths. The contact point should be T316 stainless steel with a thumb screw of T316

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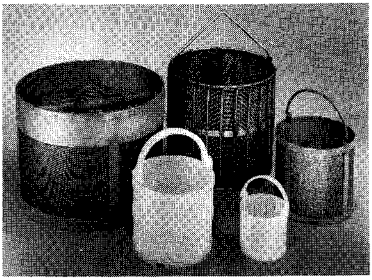

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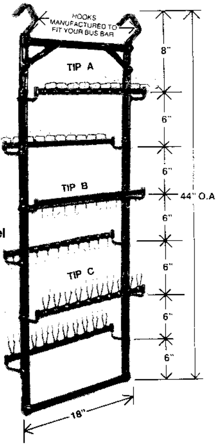

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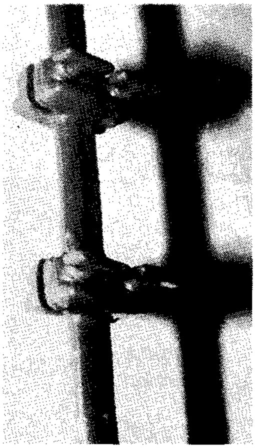


Fig. 6 Close up view of printed circuit board (PCB) tip showing only the stainless steel contact and plastisol trimmed away for a square fit for the PCB (two-point contact).

with a Teflon tip, thereby creating a positive contact with minimum plating buildup. The most commonly used thumb-screw size is 3/8–16. Some other sizes are 1/4–20, 5/16–18, 3/8–12.

The spine for PCB rack is fabricated out of copper with stainless steel reinforcement or bracing. Some PCB racks are fabricated entirely out of T316 stainless steel. All PCB racks have a top thumb screw, which securely fastens the rack to a work bar, this top thumb screw is stainless steel, plastisol coated, and is bigger than the screw that holds the board. The top thumb screw also is held in place with the added support of a threaded top nut. This threaded top nut is needed to provide additional torque support for the top thumb screw when tightening the rack to the work bar.

PCB cleaning can be done in a slotted basket. The basket should have 1/4-in. spacing between slots, be fabricated out of stainless steel, or be plastisol- or Halar-coated steel.

Halar is a highly protective coating with high temperature characteristics, this coating is much more expensive than plastisol.

In the case of very flexible contacts, it is necessary to design racks for each individual operation depending on parameters that are specific to each PCB operation. Some PCB racks have been designed with adjustable spine or cross members to accommodate different size boards in each production process.

PCB racks after a period of time will accumulate plating buildup in the contact area and will need to be repaired to continue to be productive. The PCB racks are repaired by stripping off the metal buildup and plastisol, repairing and cleaning the contact area for corrosion, and fixing the spine. The rack is then plastisol coated and trimmed to customer specifications.

The contact area on a PCB rack is a slot with a contact point between the thumb screw and contact point. This slot is a specified width and the outside of the slot can be V-shaped to help with the racking of the board.

Electroless Nickel

Plating racks designed for electroless nickel can be as simple as using a strand of copper wire to hold the piece to be finished. Stainless steel contacts can also be utilized.

Electropolishing

Electropolishing racks can be grouped in the category of a rack that needs positive contact, usually a titanium tip, because of the need for chemical resistance. Copper spines are still used and the rack is plastisol coated. Racks should hold the work so that gas pockets will be eliminated.

FILTRATION AND PURIFICATION OF PLATING AND RELATED SOLUTIONS AND EFFLUENTS

by Jack H. Berg

Serfilco Ltd., Northbrook, Ill.

This introduction reflects the response needed by platers for quality control, to meet just-in-time deliveries, and to achieve zero rejects. It also addresses the need for platers to continue to reduce solid waste after neutralization and employ filtration wherever possible to recycle or lengthen the service life of cleaners, etchants, and rinses.

Filtration usually includes the use of carbon for undesirable organic impurity removal, which years ago also doubled as a filter media along with other forms of filter aids.

Today's acceptance of granular carbon in many situations has lessened the need for powdered carbon and almost eliminated the weekly or monthly batch purification treatment. There are, however, some occasions when powdered carbon may be the only answer, and for that reason a separate piece of equipment held aside for such a need should be considered.

Platers who appreciate the value of filtration must first understand that it is not as much an art as it is a science. The requirement of a science is to have an orderly body of facts, facts that can be correlated and anticipated results yielded. Although there has been some work done in this area over the last 5–10 years, platers must still rely on experience to a great extent.

In the past, it has been suggested that the plater decide the level of quality sought and, using statistical quality control, determine if this goal has been achieved. It is further recommended that the plater needs to know the parts per million of contamination (solids) so that the necessary size or dirt-holding (solids) capacity of the filter could be established. The plater must also know the nature of the solids, which would be critical to success. Slimy, stringy, or oily contaminants blind a dense filter media surface quickly, whereas coarse, grainy, sandlike particles build a thick cake and still allow solution to pass, which provides for continued solid/liquid separation.

By first assessing these factors, platers can ascertain what results can be achieved. For example, slimy solids would require more surface area, whereas gritty particles could get by with less area (i.e., less solids-holding capacity).

However, all filter media are not manufactured in the same manner, for instance, filter paper, cloth, and plastic membranes provide a single junction to stop solids. Filter aids can enhance the ability of the filter media by creating a porous cake, which improves surface flow, but to really be successful a continuous mixing of filter aid and solids must be coordinated to maintain suitable porosity.

Other types of filter media can provide the necessary junction to stop solids but are built in such a manner as to achieve results from a combination of surfaces or juncture points, which achieve the solids retention by impedance. Thus, it is possible for continuous solid/liquid separation to be maintained over a longer period of time.

Most filter media are rated according to the size of particles that they are capable of stopping. Such a rating is based on laboratory tests and expressed in micrometers. A coarse media would be 100 μm; a dense media would be 10, 5, or 1 μm. The number suggests that at an efficiency level of 85 to 99%, all such particles would be stopped, whereas if the micrometer retention level is expressed in "absolute" ratings, 100% of the stated micrometer size and larger sizes would be removed. It further stands to reason that the coarser media will offer more solids-holding capacity, and the denser media will offer less solids-holding capacity.

Next we discuss where these troublesome solids come from and how they can be most effectively removed.

DIRT LOAD

The "dirt" (impurities) in a working plating bath can come from drag-in, anodes, water, and airborne sources. For their efficient removal, the system must be designed for the amount and type of contaminants present in the plating tank; these vary for each installation. Even without prior operating experience, an estimate of the dirt load can be made by reviewing the cleaning and plating processes to select and size the equipment needed.

A filter with insufficient dirt-holding capacity will require frequent cleaning or servicing. The rapid pressure buildup in the system as solids are retained increases the stress and wear of pump seals. By minimizing the dirt load, maintenance of the filter and pump can be reduced considerably. Even after thorough cleaning and rinsing, some solids and contaminants cling to parts, racks, and barrels. Thus, they are dragged into the plating solution. The amount of drag-in contamination depends primarily on the type of parts, plating method (rack or barrel), cleaning efficiency and rinsing cycles.

In most plating plants, the type and amount of parts being processed may vary considerably. For trouble-free operation, the filtration system should be designed for the heaviest work load and most difficult-to-clean parts. Drag-in contamination with barrels is high, due to incomplete draining of cleaners and difficulty in rinsing of loads. Filtration and purification on automatic barrel lines must be continuous, and equipment must be of sufficient size to minimize servicing and work interruption.

The amount of drag-in can often be reduced by improving the pretreatment. With the conversion of many vapor degreasing processes to aqueous cleaning, proper maintenance of cleaners and electrocleaners is of greater importance, particularly with machined or buffed parts carrying oil and lubricants. Recirculation and coalescing with an overflow weir on cleaner tanks will effectively skim off oil and scum, which would quickly foul the filter medium and carbon. More effective descaling will minimize the dirt load. Several counter-current rinse tanks and a final spray rinse with clean water will also reduce the drag-in contamination. Due to the nature of the cleaning process, contamination of the solution with organic soil (oil, wetting agents) and/or inorganic (metallic) compounds is sometimes unavoidable. These can generally be controlled by carbon treatment at the rinse tank before plating.

Filterability depends on the nature, amount, and size of suspended particles, which, in turn, are contingent upon the type and chemistry of the plating solution. Generally, alkaline solutions, such as cyanide baths, have slimy or flocculent difficult-to-filter insolubles, whereas most acid baths contain more gritty solids, which are relatively easy to filter even with a dense filter media. A quick test of a representative sample with filter paper in a funnel will determine the nature and amount of solids present. This test will also indicate the most suitable filter medium. Bagging of soluble anodes will materially reduce the amount of sludge entering the plating bath. Airborne dirt from ceiling blowers, motor fans, hoists, or nearby polishing or buffing operations may fall into the plating tank and cause defective plating. Good housekeeping and maintenance will, of course, reduce dirt load and contamination of the plating solution.

Prevention of deposit roughness is perhaps the foremost reason for filtering plating solutions. Better covering power with less chance of burning is also achieved with a clean bath. In addition to suspended solids, the plater also has to contend with organic and inorganic (metallic) impurities, which are introduced into the solution primarily by drag-in. If this contamination is allowed to build up, it will affect deposit appearance. Continuous or periodic purification of the solution with activated carbon and/or low-current-density electrolysis (dummying) will often remove these impurities before a shutdown of the plating line becomes necessary.

The trend of Environmental Protection Agency (EPA) regulations is to severely restrict the amount of suspended solids and dissolved metal impurities in wastewater discharged to sewers and streams. To comply, plating plants have had to resort to some chemical treatment of their effluents to precipitate the metals as hydroxides. The filtration of these hydrated

sludges is difficult and requires special separation equipment. Closed-loop systems, recycling, and recovery are being employed and require greater attention to filtration and purification.

Most filtration systems consist of a filter chamber containing the filter media and a motor-driven pump to transfer or circulate the solution from the plating tank through the filter. The many filters and pumps on the market today make it possible to select and justify a cost-effective filter system for each and every solution, regardless of volume.

When engineering a filter system for a plating installation, it is necessary to first establish the main objectives, such as: high quality finish—maximum smoothness and brightness; optimum physical properties—grain size, corrosion, and wear resistance; or maximum process efficiency and control—covering power, plating rate, purification, and clarification.

Then the following factors must be considered before selecting the size and materials needed for the filter media, chamber, pump, and motor:

1. Dirt load—suspended solids, size, kind, and amount; also soluble organic and inorganic impurities.
2. Flow rate—turnovers per hour for a given volume of solution necessary to maintain clarity.
3. Frequency of filtration and purification—batch, intermittent, or continuous required to remove dirt and contamination and filter servicing interval desired.

When agitating solutions with air, a low-pressure blower is usually employed. This makes it virtually impossible to achieve good filtration of the air while keeping the solution clean, because the plating solution then acts like a fume scrubber.

If effluent regulations make it necessary to remove or reduce total suspended solids (TSS) from wastewater, the amount discharged per hour or shift can be readily determined. For instance, a 100 gal/min (gpm) effluent containing 100 ppm TSS (100 mg/L) will generate 5 lb of solids per hour, as calculated below:

$$100 \text{ gpm} \times 3.79 \text{ L/gal} \times 100 \text{ mg/L} \times 60 \text{ min/hr} (1000 \text{ mg/g} \times 454 \text{ g/lb}) = 5 \text{ lb/hr } (2.3 \text{ kg/hr})$$

Therefore, the filter must have sufficient capacity to hold approximately 40 lb of solids/8 hr of operation. A horizontal gravity filter would be the most cost efficient for this dirt load and would operate automatically; however, if dryness of the retained solids is to be achieved, then a filter press would be recommended.

Filtration and/or purification during nonproductive hours makes it possible to remove dirt at a time when no additional contaminants are being introduced into the tank, such as insolubles from anodes, chemical additions, plus that which would otherwise be dragged in from improper cleaning of the work. Again, individual tank operating characteristics and economics will determine the ultimate level of acceptable quality.

This brings up an important consideration. Contamination by organic compounds, inorganic salts, wetting agents, and oils is not removed by filtration, but by adsorption on activated carbon. Some plating solutions, such as bright nickel baths, generate organic byproducts during plating. It cannot be assumed that both types of contamination increase at the same rate. A batch treatment, therefore, may eventually become necessary, either because of insoluble or soluble impurities. A check of clarity, flow rate, and work appearance and a Hull cell test will indicate the need for transfer filtration and/or carbon treatment.

If analysis shows that the concentration of insolubles (in ppm) has increased, it would indicate that the solution is not being adequately filtered. Therefore, transfer pumping of the solution through the filter should be employed as the quickest way of getting all the solids out at once and returning the clean solution to the plating tank. Soluble impurities can be detected by inspection of the work on a Hull cell panel. Pitting, poor adhesion, or spotty appearance indicates the need for fresh carbon. Here again, it may be desirable to completely batch treat the solution to restore it to good plating quality; however, since this necessitates shutting down the plating line and requires considerable labor, every effort should be made to maintain solution clarity and purity continuously, without having to resort to such batch treatment.

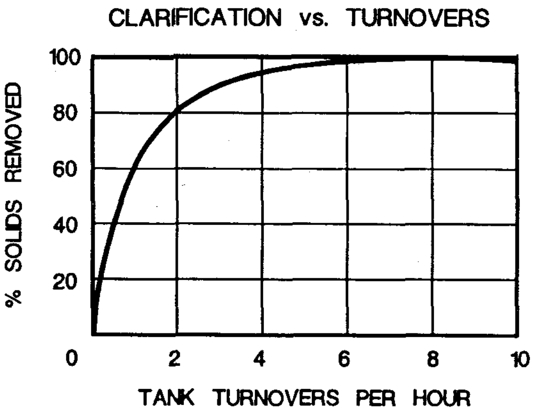


Fig. 1. Higher clarification is achieved by, increasing the number of tank turnovers per hour.

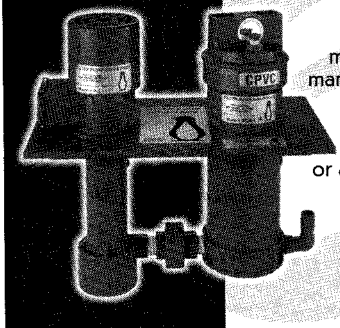
FREQUENCY OF FILTRATION AND PURIFICATION

Since it is desirable to plate with a solution as free of suspended solids as possible, the quickest way to achieve clarification is by transfer pumping all of the solution from one tank, through a filter, to another tank (batch treatment); however, to maintain both clarity and uniform deposit quality, continuous recirculation through a filter is most effective. Although continuous filtration is more desirable, there are some plating installations that require only intermittent filtration, because relatively small amounts of solids are present. In other cases, it is necessary to filter and purify the bath continuously, even when not plating.

A high flow rate is essential to bring the particles to the filter as quickly as possible and to prevent settling of dirt on parts being plated. Although plating in a solution completely free of solids would be best, this ideal can be approached only in the laboratory. Some contamination always exists, and must be accepted. Continuous filtration at a high flow rate can maintain a high level of product quality by keeping suspended solids to a minimum. As Figure 1 indicates, four to five complete tank turnovers effectively remove 97% of all filterable materials if no additional solids are introduced. Since, in many installations, the rate at which contamination is introduced is higher than the rate at which it is removed, the impurities and solids gradually increase with time unless filtration is continued even during nonplating periods.

The greater the turnover rate, the longer the plating bath can be operated before the reject rate becomes too high and batch (transfer) filtration is necessary. In practice, contaminants are not introduced at a steady rate; for instance, most are introduced with the parts to be plated and, therefore, at the moment of immersion the degree of contamination is sharply increased until it is again reduced by the action of the filters. It then increases again when more parts are put into the tank for plating.

Figure 2 indicates the reduction in flow caused by the dirt buildup in the filter on a day-to-day basis, where one week's filtration would be effected before service of the filter becomes necessary. This reduction in flow rate could also have been representative of a longer time interval between filter cleanings. Graphically, it indicates why platers may experience roughness at varying intervals in the plating filtration cycle. The amount of solids increases in the tank as the flow rate decreases to a level that may cause rejects. After the filter is serviced, the increased flow rate agitates any settled solids. Therefore, it is advisable to delay plating of parts until the contaminant level is again reduced by filtration to within tolerable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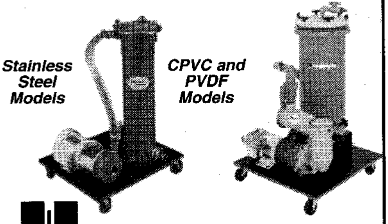

Stainless Steel Models
CPVC and PVDF Models

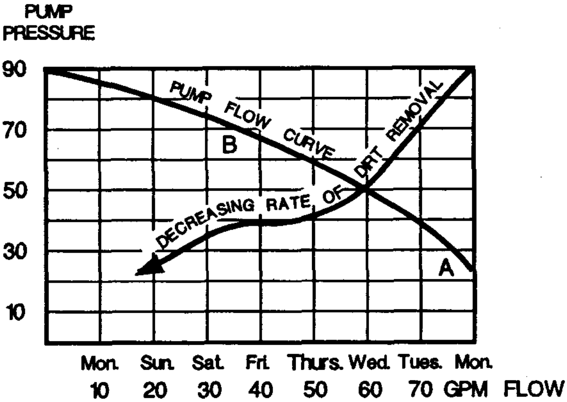


Fig. 2. Clean filter at point A will flow 4,800 gph and dirt removal is maximum. Flow rate has dropped to 2,000 gph at point B. Situation applied to a 2,000-galtank would represent a reduction in flow from almost 2.5 tank turnovers per hour to one tank turnover per hour during a time interval of one work week. If filter continued to operate without servicing, the rate of dirt removed would soon be less than the rate of dirt introduced into the system. The time interval during which the filter is performing effective filtration will be determined by job conditions.

limits. This phenomenon generally occurs in a still tank, since the dirt has more chance to settle. For this reason, when the solution is pumped into a treatment tank, sludge may be found on the bottom of the plating tank.

Dirt in an air-agitated tank can settle any time after the air is shut off. If carbon and/or a filter aid is used in the filter during the continuous filtration cycle, it should be borne in mind that, as these solids are collected on the media, the pressure increases appreciably, reducing the initial flow rate by almost 25% and the overall volume pumped through the filter by as much as 50% before servicing is necessary (Fig. 3). Frequent laboratory checks will verify the amount of insolubles in the plating tank, which will tell whether a uniform degree of clarity is being maintained or whether it is increasing slowly toward the reject level. More frequent servicing of the existing filtration equipment will increase the total volume pumped and, in turn, maintain the lowest possible level of contamination and minimize the need for batch treatment.

It is, therefore, necessary for the plater to determine the particle size to be removed and then select the media that provides the most solids-holding capacity. Then, knowing the efficiency of the media, multiply it by flow rate so that all of the solution passes through the filter in a certain period of time, such as 1 hr or 1 min. Note the small amount of solution that is filtered in 5 min if a rate of one turnover per hour is used (Fig. 4) as compared with the amount that would pass through at a rate of ten turnovers per hour (assume a 100-gallon solution):

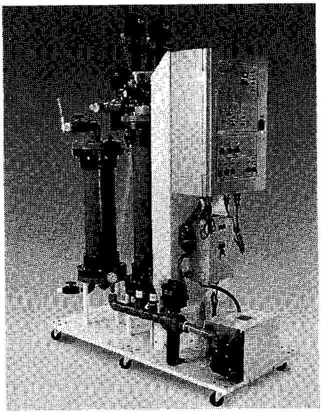
At one turnover per hour,

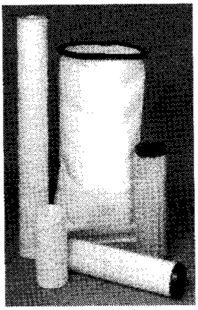
$$1 \times 100 \text{ gal/60 min} = 1.6 \text{ gpm} \times 5 \text{ min} = 8 \text{ gal filtered}$$

At ten turnovers per hour,

$$10 \times 100 \text{ gal/60 min} = 16.6 \text{ gpm} \times 5 \text{ min} = 83 \text{ filtered}$$

The point here is that if nearly the entire solution is turned over every 5 min, then the plating bath will exhibit a high degree of clarity and purity. The net result should be fewer rejects caused by occlusion of particulate matter in the deposit.





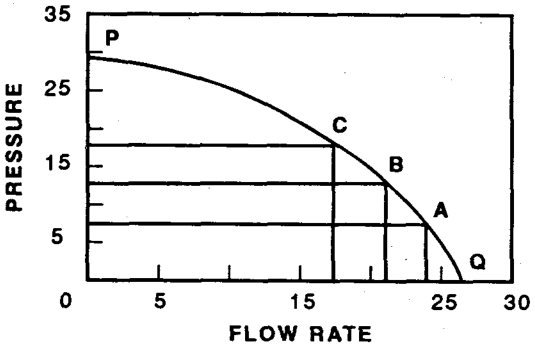


Fig. 3. Typical flow versus pressure curve. Q represents the maximum open pumping against no restriction, whereas P represents the pressure that the pump can develop at zero flow. A might indicate the pressure drop across a depth type media or a bare support membrane, whereas points B and C indicate the reduction in flow caused by the addition of filter aid and carbon, respectively.

In modern electroplating, no area that can result in improved quality should be overlooked. The plater can use the principles of high tank turnover and solution velocity to his advantage in his quest for zero rejects.

During recent years the flow rate through the filter, or tank turnover as it is referred to, has increased to two or three per hour or higher for most plating solutions (see Table I). This means that 1,000 gallons require a flow rate of at least 2,000 to 3,000 gallons per hour (7.6–11.5 m^3/hr); however, platers should recognize the need and employ turnovers of 10 or even 20 times per hour when all solids must be removed (see Fig. 1).

Alkaline solutions may require even higher flow rates for more effective solids removal by recirculation. Depending on the filter medium and its retention efficiency, flow rates in the range of 0.5 to 2 gpm (2 to 8 Lpm) per square foot of filter surface area are obtainable. Although 5 gpm per 10-in. (25-cm) cartridge is permissible, flow rates under 1.5 gpm per cartridge offer better economy. In fact, at a given flow rate with a cartridge filter, servicing, cartridge cleaning, or replacement can be reduced significantly by increasing the size of the filter. For example, *if the size of the filter was multiplied by four the annual amount of filter cartridges consumed would be cut in half and the filter itself would operate unattended for at least four times as long before cartridge cleaning or replacement was necessary.* This is an important consideration to reduce media consumption.

It has also been found that the effective life of surface filters may often be tripled by doubling the surface. By increasing the dirt-holding capacity and reducing the frequency of filter servicing and replacement, the cost of filtration on a per month or per year basis is substantially reduced.

TYPES OF FILTER SYSTEMS

After estimating the dirt load and determining the flow rate and filtration frequency required, a choice of filter method and medium must now be made. The most common types of filters used in the plating industry are discussed below. These filters may be placed inside or outside the tank.

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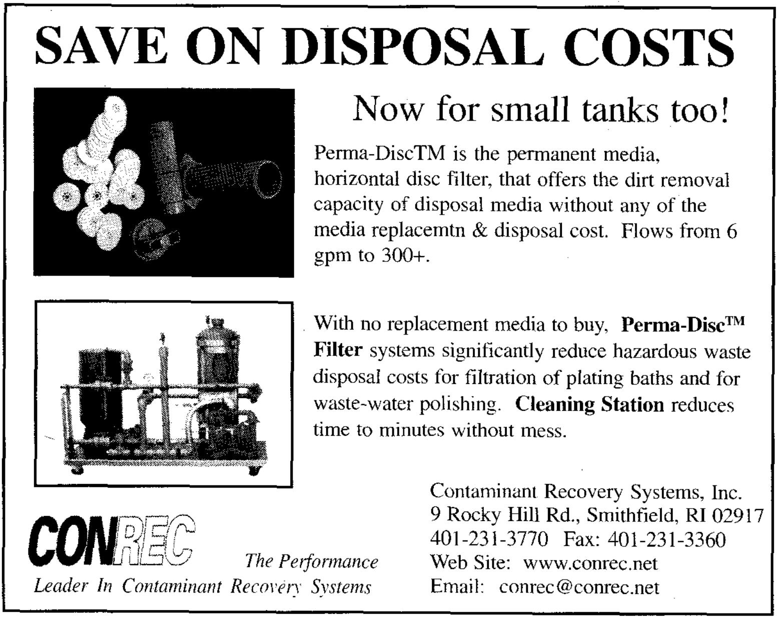

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Table I. Guide to Filtration and Purification of Plating Solutions

Process	pH	Temp. (°F)	Filtration	Turnovers/ hr[a]	per 100 gal.[b]		Media Fiber/ Core[c]	Porosity (μm)[a]	Carbon Treatment
					Surface Area	No. Filt. Carts.			
Anodizing	1	60–90	Optional[d]	1–2	3.5	1	U/U	15	No
Nickel acetate seal	5.5	200	Desirable[d]	2–3	7	2	U/S	15	Batch/Continuous
Brass, bronze	10	100–200	As required[d]	2–3	7	2	U/U	15	No
Cadmium	12	100	As required[d]	2–3	7	2	U/U	30	No
Chromium, hexavalent	1	110–130	Optional[d]	1–2	3.5–7	1 or 2	M/U or glass[e]	15	No
Chromium, trivalent	2–3.5	75	Continuous	2–3	10.5	3	U/U	1–5	As needed
Copper acid	1	75–120	Continuous	2–3	10.5	3	U/U	15	Batch/Continuous
Copper cyanide	11–13	70–150	Continuous	2–3	10.5	3	U/U	15	Batch/Continuous
Copper, electroless	14	100–140	Continuous	1–2	7	2	U/U	3	No
Copper fluoborate	1	70–120	As required	1–2	3.5	1	U/U	15	As needed
Copper pyrophosphate	8–9	110–130	Continuous	2–3	7	2	U/U	10–20	As needed
Gold acid	3–6	80–125	Continuous	2–3	7	2	C/U	1–5	Periodic
Gold cyanide	7–12	75	Continuous	2–3	7	2	C/U	5	Periodic
Iron chloride	1	195	Continuous	2–3	7	2	U/U	15	Yes
Lead fluoroborate	1	100	Continuous	1–2	3.5	1	U/U	15	No
Nickel, bright	3–5	125–150	Continuous	2–3	7–10.5	2 or 3	C/U	15–30	Yes
Nickel, semi-bright	2–5	130	Continuous	2–3	7	2	C/U	15	Yes
Nickel chloride	2	120–150	Continuous	2–3	7	2	C/U	15	Yes
Nickel, electroless	4–11	100–200	Continuous	2–3	7	2	U/U	15	As needed
Nickel sulfamate	3–5	100–140	Continuous	2–3	7	2	C/U	15	Yes
Nickel, Watts	4	120–160	Continuous	2–3	7	2	C/U	15	As needed
Nickel–iron	3.5–4	135	Continuous	2–3	7–10.5	2 or 3	C/U	15–30	Yes
Rhodium acid	1	100–120	As required	1–2	3.5–7	1 or 2	U/U	5	Periodic
Silver cyanide	12	70–120	Continuous	2–3	7	2	C/U	5	Periodic
Tin acid	0.5	70	As needed[d]	1–2	3.5	1	U/U	15	As needed
Tin alkaline	12	140–180	As needed[d]	3–4	10.5	3	C/U	30	No
Tin–lead (solder)	0.5	100	Continuous	1–2	3.5	1	U/U	15	Periodic
Tin–nickel	2.5	150	Continuous	1–2	7	2	U/U	15	Yes
Zinc acid chloride	5–6	70–140	Continuous	2–3	14	4	U/U	15	As needed
Zinc alkaline	14	75–100	As needed[d]	2–3	10.5	3	U/U	30–50	Optional
Zinc cyanide	14	75–90	Continuous	2–3	10.5	3	C/U	30–100	No

[a] Increased turnover allows for use of coarser media to increase solids holding capacity. As many as 20 turnovers have been used on critical applications.

[b] (Surface area measured in sq. ft.) Increasing number of cartridges improves efficiency, reduces pump velocity and reduces amount of cartridges used.

[c] C - Cotton, U - Polypropylene, S - Stainless Steel. Depending on tank size and space, select appropriate in-tank or out-of-tank pump with nonmetallic solution contact. Either sealless magnetic or mechanical seal horizontal pumps are most common. For electroless plating solutions, a water flushed double mechanical seal pump, or vertical sealless pump is required.

[d] For best results, continuous filtration should always be considered.

[e] Immersion-test filter media fibers to select most cost effective.

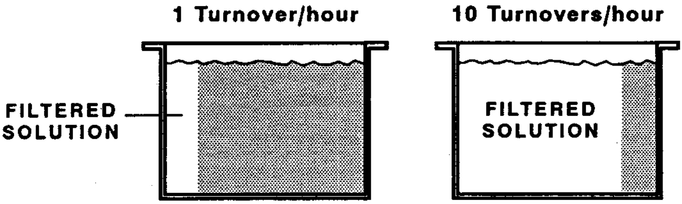

Fig. 4. Comparison of filtered volumes for 100 gal of solution after 5 min of filtration at respective turnover rates.

In-Tank Considerations:

Tank space
Motors located over fumes
Limited size of filter (less service life of media if used on pump suction)

Out-of-Tank Considerations:

Remote possibility for easy service
Employ sealless magnetically coupled pumps or direct-drive with single or double water-flushed seal
More suitable for use with slurry tank for chemical or filter aid/carbon addition or backwashing
Larger dirt holding and flow capacity from cartridges or surface media

Cartridge Filters

Cartridges offer both surface and depth-type filtration characteristics, providing various levels of particle retention at different efficiencies (nominal and absolute), manufactured in natural and synthetic (plastic) materials to provide a wide range of chemical resistance, flow rates, and particle retention capacities. Pleated-surface media offer initially higher flow rates, are available with a choice of porosities (usually in the denser range), and are sometimes given an absolute particle-retention rating.

Depth-type media are available in 1- to 100-μm particle retention and, because of the variety of porosities available, they are sometimes best suited to handle high-dirt-load conditions. This is a result of the manner in which the depth-type cartridge filter is manufactured. Basically, it consists of a series of layers, which are formed by winding a twisted yarn around a core to form a diamond opening. The fibers, which are stretched across the diamond opening, become the filter media. Succeeding layers lock the previously brushed fibers in place and, since there is the same number of diamond openings on each layer, the openings become larger due to the increase in circumference; other fiber-bonded types also increase density across the depth of the media.

During filtration, the larger particles are retained on the outer layers of the cartridge where the openings are large, whereas the smaller particles are retained selectively by the smaller openings on succeeding inner layers. This, then, makes it possible for an individual cartridge to have a dirt-holding capacity equal to 3.5 ft^2 of surface filter area of the same density. Cartridges having a 15- to 30-μm retention will often hold 6 to 8 oz of dry solids before replacement is necessary, whereas cartridges of 10 μm down to 1 μm will have a dirt-holding capacity of perhaps 3 oz to less than 0.5 oz. These figures merely indicate that the coarser cartridges have greater dirt-holding capacity, are more economical to use, and can be used longer before replacement.

Also, as pointed out earlier, dirt loads vary from tank to tank, and cartridges should be selected according to the individual requirements. A dense cartridge having less dirt-holding

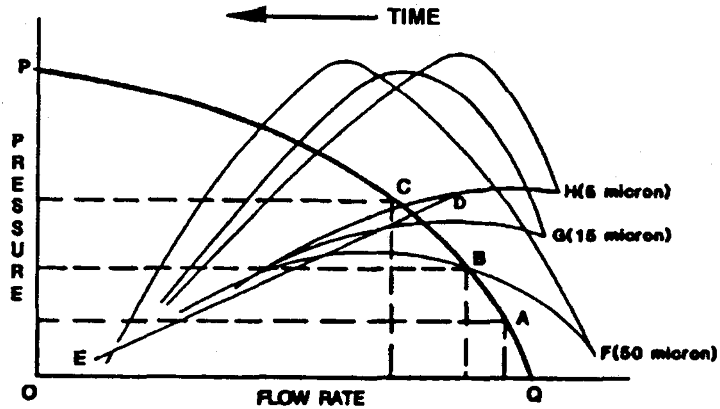

Fig. 5. In comparison with Figure 3, these curves show the effect on the rate of contaminant removal by using a coarser filter medium. Dirt pickup may increase for a while due to more effective filtration; the solids pickup increases the filter medium density after which it decreases as flow rate is also reduced. A, the highest possible flow rate; B, addition of filter aid reduces flow; C, addition of carbon; D, maximum dirt particle removal; E, no flow.

capacity will load up more quickly, increasing the pressure differential and, therefore, reducing the flow (Fig. 5). Using coarser cartridges (greater than 30 μm on zinc, for example) that have greater dirt-holding capacity and a longer service life may make it possible to clarify the plating tank more quickly because of the high obtainable flow rate. This will be accomplished at less cost. Usually two cartridges (three on zinc, tin, and cadmium) are recommended for each 100 gal of tank capacity.

The pump should provide a pumping rate of at least 100 gph (two tank turnovers per hour) for each cartridge. Usually, a cartridge life of 6 weeks on nickel or 4 weeks on zinc can be expected, with some tanks running as long as 12 weeks; however, much depends upon dirt load, hours of plating, and so on. With cartridges, a higher dirt load can be retained in the filter chamber because of the coarseness of the filter media. Higher flow rates can usually be employed during the entire lifespan of the cartridge. This is due, in part, to the higher head pressures of pumps employed without chancing the rupture of a cartridge. Since all of the dirt is retained on and in the cartridge, the cartridge filter can be turned off and on at will, unless the cartridges are precoated. Cartridges are changed with very little maintenance expense and no solution loss; however, simplicity of use is perhaps the most predominant single factor in their selection.

Precoat Filters

Precoated filters consist of a membrane (leaf, sleeve, or screen) such as paper, cloth, ceramic, sintered metal, wire mesh, or wound cartridges. These membranes support the diatomite or fibrous-type filter aid, which has been mixed in a slurry of water or plating solution and picked up by the membrane openings. The dirt is retained on the outer surface of the cake. When the pressure has increased and the flow rate has decreased to a point where filtration is no longer efficient, the dirt and cake are washed from the membrane. Paper membranes are discarded and replaced.

The ability to obtain long runs is dependent upon proper selection of the foundation media, coupled with a coarser-than-usual nonfibrous-type filter aid (to be used where possible). Periodic (daily, if necessary) additions of small quantities of filter aid should be made to lengthen the cycle between servicing. The dirt-holding capacity of this type of filter is usually measured in square feet of filter surface. (If the standard 2.5 × 10-in. long cartridge is used, its outer surface when precoated would be equivalent to about 0.50 to 0.67 ft^2 of area.) Flow rate and dirt-holding capacity of the various precoated membranes or cartridges would be about equal.

Before precoating, the operator should know or determine the filtration area to be covered. The amount of filter aid used depends on its type and on the solution being filtered. Generally, 0.5 to 2 oz/ft^2 of filter is sufficient. The manufacturer's recommendations for type and amount of filter aid should be followed if optimum results are to be obtained. A slurry of filter aid and plating solution or water is mixed in a separate container or in a slurry tank, which may be an integral part of the filtration system. The slurry is then caused to flow through the filter media and create a filter cake.

Usual flow rates range from 0.5 to 2 gpm/ft^2 of filter surface. A lower flow rate improves particle retention and smaller particles will be removed. It should be pointed out that, although there may be a wide range in flow rate, the range of selectivity of particles being removed is between 0.5 and 5 μm, which is the most significant difference between precoat and depth-type cartridges and offers a wider choice of porosity.

Buildup of cake should be gradual, and recirculation should continue until the solution runs clear. Cake should be dispersed uniformly across the media before the plating solution is allowed to flow across the filter. A slurry tank piped and valved into the filtration system becomes a convenient and versatile piece of equipment. The slurry may be prepared with plating solution, rather than water, to avoid diluting critical mixtures. Via valving, the solution is drawn into the slurry tank for sampling, preparation of slurry, and chemical additions. Similarly, the solution is returned to the plating tank. This method eliminates the necessity of transfer hoses between tanks, and the subsequent risk of loosening the cake or losing pump prime. The integral slurry tank is also a convenient storage for backwash water.

Precoat Backwash Filters

These filters operate the same as, and have the same functional purpose as, ordinary filters with the further advantage that they can be cleaned quickly by reversing the flow through the filter media. Backwashing the filter aid and dirt away makes the media available for prompt repeat precoating. The basic advantage is that the filter chamber need not be opened each time the filter requires cleaning.

Finer grades of filter aid may be precoated on top of the coarse filter aid when fine powdered carbon is to be used continuously. Here again, periodic (daily, if necessary) additions of small quantities of filter aid should be made to lengthen the cycle between backwashing. The media may be cleaned automatically with sluicing or using other devices. Iron hydroxide sludges can be dissolved by circulating dilute hydrochloric acid from the slurry tank; additional manual cleaning may also be required occasionally.

Some disadvantages of precoat and backwashing are the possible loss of solution, increased waste treatment loading, and the possibility of migration of filter aid and carbon into the plating tank. The use of rinse water for backflushing will reduce waste treatment loading; however, if evaporation is used to control drag-out, this may interfere with evaporator operation and the economies achieved by using this equipment.

Sand Filters

Using sand as the filter media, the pump and filter operate like a precoat surface filter and backwash like a precoat without the need of additional aid to achieve fine particle retention. Performance can be acceptable based on recirculation turnover rates, with the basic disadvantage coming from a smaller surface area, which increases the need for frequent backwashing and resulting solution loss to maintain the desired flow rate (turnover required).

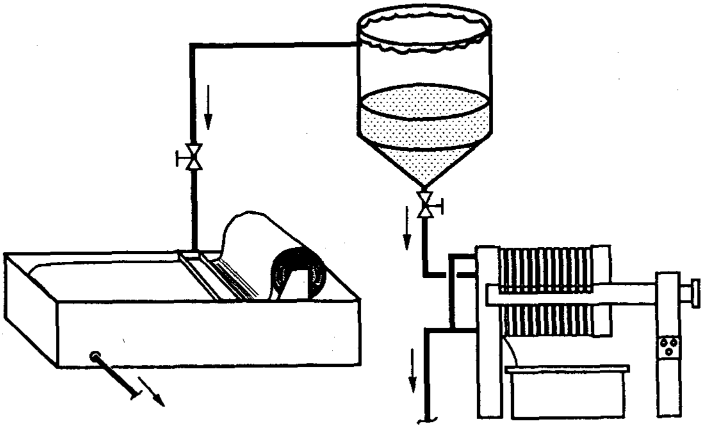

Fig. 6. Automatic disposable fabric filtration system for neutralized solid/liquid waste separation.

Horizontal Fabric and Screen Filters

These filters are especially well suited for the continuous dewatering of hydrated metal sludges resulting from the neutralization of plating wastewater prior to sewer discharge. They are also effective in removing accumulated iron sludge from phosphating tanks.

In one such system (Fig. 6), the waste containing 1 to 3% solids is first allowed to settle in a cone-shaped tank. The supernatant liquid drains into a head box, which directs the flow across the filter medium (paper or plastic) supported by a motor-driven conveyor belt. The liquid passes through the disposable fabric by gravity flow into a receiving tank below. When the pores of the media become clogged, the liquid level rises and a float switch activates the belt drive. Fresh media is fed over the tank and filtration is continuous. The cake on the fabric is allowed to drain before it is dumped into the sludge box. Gravity drain or an immersion pump empties the filtered water from the tank. Cycling and indexing of the filter are automatic. The occasional replacement of the filter fabric roll is the only labor required. The sediment in the bottom of the cone can also be dewatered periodically by filtration on the fabric. Other systems feature pressure or vacuum filtration. The sludge cake contains from 5 to 35% solids, depending upon the equipment and type of cake. Cakes can be further treated by air evaporation or with heat for dry disposal. The filtrate can be discharged to the sewer if it meets local effluent regulations or can be recycled through the system.

The performance of the unit can be improved greatly by the addition of coagulants and flocculating agents, such as polyelectrolytes, which increase the amount of solids, particle size, and settling rate. The flow rate is approximately 1 gpm/ft^2 with 90 to 95% solids retention; with coarse filter media, flow rates increase up to 10 gpm/ft^2. Filter aid can also be precoated to improve retention. The filter media is available in porosities of 1 to 125 μm and rolls 500 yd long. Carbon-impregnated paper is used for purification and removal of organic contaminants. The unit must be sized properly for each application to operate efficiently and with a minimum media cost. Steel, coated, stainless steel, or plastic units are available for corrosive solutions.

BATCH AND CONTINUOUS ACTIVATED-CARBON PURIFICATION

Virtually all plating solutions and some cleaners or rinses at some time will require purification via the adsorption of impurities on activated carbon. Those solutions that contain

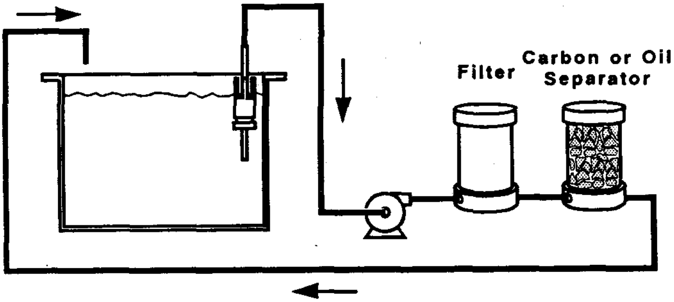

Fig. 7. Skimmer, pump, and prefilter with carbon or free oil separator.

wetting agents require the most carbon; when oil is introduced into the bath, the carbon is dispersed throughout the solution and clings to the parts, causing peeling or spotty work. Solutions that do not contain wetting agents have a tendency to float oil to one corner, depending on the recirculation set up by the pump, and in this case the oil may be removed with a skimmer or coalescer (see Fig. 7).

The choice of purification method depends on the size of tank and amount of carbon required and also on other available auxiliary equipment. Generally, carbon cartridges are used on small tanks (up to a few hundred gallons), and the bulk or canister type or the precoat method is used for the very largest tanks. The canister type is also used on the larger tanks supplemental to surface or depth-type cartridges or on certain automatic filters to supplement the amount of carbon.

Batch Treatment

The quality of the carbon is important and special sulfur-free grades are available. The average dosage is 10 lb of carbon to treat 500 to 1,000 gal of warm plating solution. At least sixty minutes contact time with agitation should be allowed, followed by some settling before transfer clarification can be achieved.

Continuous Purification

A separate purification chamber holding bulk granular carbon, a carbon canister, or cartridges offers the most flexibility in purification treatment. By means of bypass valving, the amount and rate of flow through the carbon can be regulated to achieve optimum adsorption of impurities without complete depletion of wetting agents and brighteners in the plating bath. It provides for uninterrupted production and fewer rejects. When necessary, the carbon can be changed without stopping filtration of the bath. Filtration should always precede carbon treatment, to prevent dirt particles from covering the carbon surfaces.

CONTINUOUS CARBON TREATMENT METHODS

Carbon Cartridges

Cartridges containing up to 8 oz of either powdered or granular carbon for every 10 in. of cartridge length are available and will fit most standard replaceable filters that employ this type of media. They may include an outer layer, which serves as a prefilter, and an inner layer, which serves as a trap filter. These handy cartridges are ideal for small filter chambers because of the ease and convenience of quickly replacing a conventional depth tube with the carbon tube when necessary. They may also be used with submersible filter systems, but in this case the flow rate could be greatly reduced.

Carbon Canister

Granular carbon may be used in ready-to-use chambers, each with a number of canisters holding up to 10 lb of granular carbon, and placed in line to the tank. A built-in trap filter eliminates migration of the carbon. Prefiltration ahead of the purification chamber will prevent solids from coating the surface of the carbon in the canister, assuring maximum adsorbency. The carbon in the canister can be replaced when its adsorption capacity has been reached. This method of separate purification offers the most flexibility. Any portion or all of the filtrate can be treated as needed by means of a bypass valve after the filter.

Bulk Carbon Method

Granular or bulk carbon is poured loosely around standard depth-type cartridge filters or sleeves, is poured into specific chambers designed for carbon, or is pumped between the plates or disks of other surface media. Since no filter aid is used, fines breaking off from the piece of carbon will have to be stopped by the surface media. Therefore, an initial recirculation cycle without entering the plating tank or recirculation on the plating tank prior to plating is desirable. This method does not alter the solids-holding capacity of depth-type cartridges, as most of the carbon will stay on the outer surface layer; however, carbon removal is not easily accomplished.

TIPS ON FILTER INSTALLATION

Filtration equipment should be installed as close to the plating tank as possible in an area that affords access for servicing. Equipment that is not easy to service will not be attended to as frequently as required, and the benefits of filtration will not be maximized. The suction line should always have a larger diameter than the discharge to avoid starving the pump (e.g., 1 in. versus ¾ in. or 2 in. versus 1.5 in.) Where it is necessary to install the equipment more than 10 to 20 ft away, check the pump suction capabilities and increase the size of the suction piping (1.5 in. instead of 1 in., or 2 in. instead of 1.5 in.) to offset the pressure loss.

Hoses made of rubber or plastic should be checked for compatibility with the different solutions. Strong, hot alkaline and certain acid solutions such as chromium are especially aggressive. The use of chlorinated polyvinyl chloride (CPVC), polypropylene, or other molded plastic piping for permanent installation is becoming more common. Some plastics are available with socket-type fittings, which are joined with solvents. Their chemical inertness and temperature capabilities are excellent. Iron piping, lined with either rubber or plastic, is ideal but usually limited to use on a larger tank capable of justifying the investment. It should be pointed out that whenever permanent piping can be used in and out of the tank a more reliable installation will exist, since there is no shifting to loosen fittings, and collapsing or sharp bending of hoses is eliminated. The suction should be located away from anode bags, to avoid their being drawn into the line and causing cavitation. Strainers on the suction are always advisable.

It is also desirable to drill a small opening into the suction pipe below the normal solution operating level on permanent installations so that, should any damage occur to the system, the siphon action or suction of the pump will be broken when the level reaches the hold (Fig. 8). This provides added safety during unattended operation. Whenever automatic equipment is operated, some provision must be made to protect against unforeseeable events that could cause severe losses. This includes some form of barrier or removable strainer to prevent the suction of parts into the pump. The addition of a pressure gauge is strongly recommended to

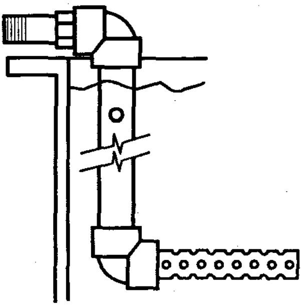

Fig. 8. Suction or dispersion piping system with strainer and siphon breaker. Drill a hole 2 in. below working solution level as a siphon breaker to prevent solution loss due to unforeseen damage to piping, pump, and so on. Chlorinated polyvinyl chloride with screwed connections offers maximum flexibility and ease in installation and may also be used on the return line by eliminating the strainer and replacing it with a longer length of pipe that is open along the full length.

determine the initial pressure required to force the solution through the filter and also to determine when the filter media needs to be replaced.

When starting up a new filter system, or after servicing an existing system, it is advisable to completely close the valve on the downstream side of the filter; in this way, the pump will develop its maximum pressure, and one can immediately determine whether the system is secure. Sometimes filtration systems are tested on a cold solution and, in turn, will leak on a hot solution and vice versa. Therefore, a further tightening of cover bolts, flange bolts, and so on may be necessary after the filter has been operating at production temperature and pressure. If pump curves are not available, one may wish to check the flow at different pressure readings to determine a reasonable time for servicing the equipment before the flow rate has dropped too low to accomplish good dirt removal.

SELECTION AND CARE OF PUMPS

by Jack H. Berg

Serfilco Ltd., Northbrook, Ill.

Since the pump is the heart of the filtration system, it must have the ability to deliver and maintain the desired flow rate and pressure as the dirt builds up on the filter medium. Proper pump and seal selection is critical and requires the following considerations:

1. Flow rate required (tank turnovers per hour in gph)
2. Location (in or out-of-tank)
3. Discharge head and distance
4. Filter medium and pressure drop
5. Solution corrosivity
6. Solution temperature

All construction materials must be compatible with the solution being pumped. In some cases, it is advisable to specify a construction material that will corrode slowly within tolerable limits if the material of ideal chemical resistance is too costly. In addition to the initial investment, careful consideration must be paid to the costs of pump operation, down time, parts, and labor. One should also consider, for each application, the relative advantages and disadvantages of the various styles.

PUMP TYPES

Horizontal centrifugal pumps (Fig. 1) are the most common pumps used in the plating industry. Usually, the only part that wears is the seal. Flow rates are high, and pressure is moderate; thus, this pump is suitable for most filtration requirements. Care must be taken when pumping liquids with a specific gravity higher than 1.0 to ensure that the motor is not overloaded. A valve on the discharge adjusts the flow and thus the required power when the centrifugal pump is working against virtually no restriction, such as when operating with a clean filter. Care is usually taken by the manufacturer to supply a sufficient amount of

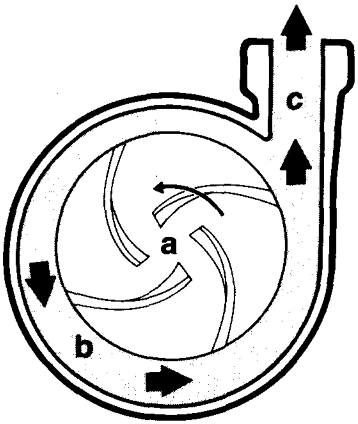

Fig. 1. Horizontal centrifugal pump. The rotation of the impeller imparts velocity to the liquid. Centrifugal force moves the liquid to the periphery of the casing and toward the discharge port. When the liquid in the impeller is forced away from the center of the liquid, a reduced pressure is produced and consequently more liquid flows forward.

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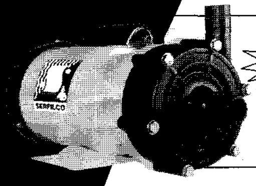

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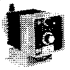

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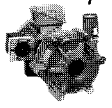

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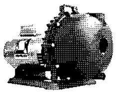

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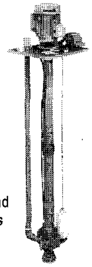

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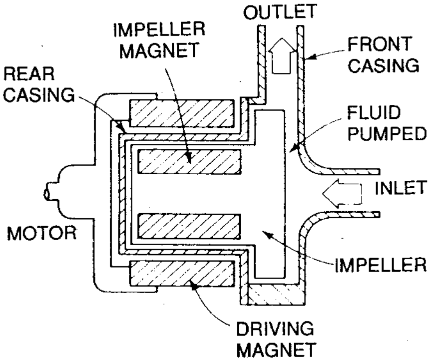


Fig. 2. Magnetic-coupled pumps can be of any hydraulic design, but they always use magnets to transmit the required driving torque.

horsepower to prevent this overloading, and also protection is provided in the motor starter. Some users de-rate the system by using a motor of lower horsepower to save on operating cost. To guard against overload, the discharge valve must be employed.

Close-coupled, horizontal pump-motor units are available in all price ranges and sizes and offer the greatest advantage in always assuring proper alignment between the pump and the motor. They are compact and, therefore, require less floor space. Long-coupled pump-motor units use standard motors and usually require an additional mounting plate to assure proper alignment. Improper alignment causes vibration of the pump and motor assembly, which, in turn, causes failure at the motor and pump bearing; it also has an adverse effect on the pump seal.

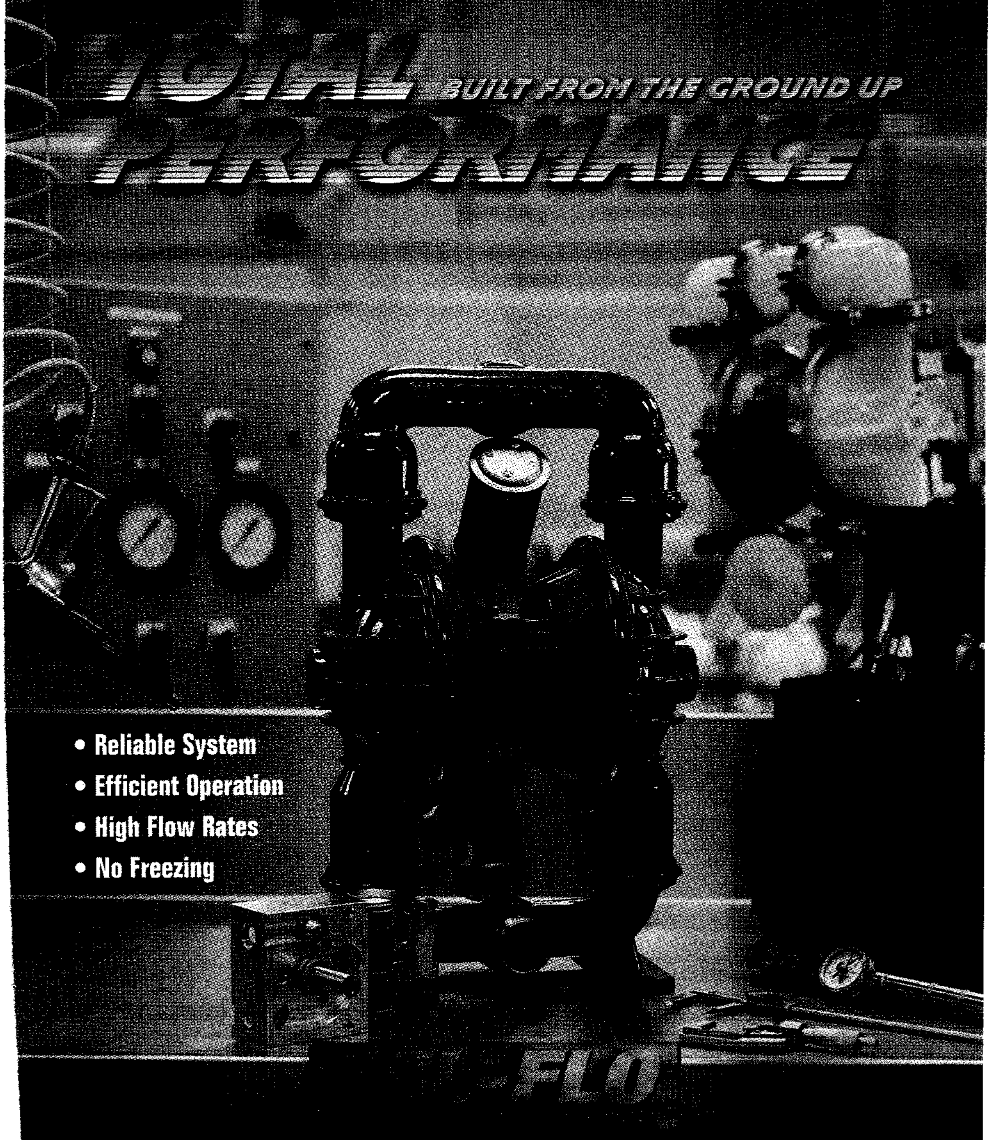
Turbine pumps are similar to centrifugal pumps in basic design. These pumps provide high-discharge head at lower flow rates than do centrifugal pumps. However, they should only handle clean, low-viscosity liquids.

Vertical sump pumps are usually of the centrifugal type and, depending upon design, may have no bearings at all. This first type is referred to as a cantilever or bearingless vertical pump. They are capable of running dry at high speed but are limited to a length of 1 ft. If pumping is initiated only after the pump casing is immersed, a suction extension will allow up to 10 ft of deep drainage from a 1-ft long cantilevered pump. Cantilever-type pumps can also be mounted external to the tank.

The short plastic cantilever pump is well suited to mixing, agitating, or transferring many types of solutions. The performance is like that of their horizontal counterpart; however, there are no wearable parts. The short cantilever shaft requires no support and has neither seals nor bearings. A double impeller prevents the solution from being pumped up the column, even at no flow and maximum head. Since these pumps are sealless and have generous clearances, they are suitable for electroless nickel and can even run dry. These pumps are said to be maintenance free.

Longer pumps require one or more bearings, which may also act as seals. Vertical pumps with sleeve bearings should be specified with as short a column length as is practical. They should be driven by 1,725 rpm motors where possible to reduce the load and subsequent wear on the bearings; however, loss of performance should be expected at 1,725 versus 3,450. For the best results, bearings should receive fresh water rather than product flush. Long pump columns with multiple bearing sets demand perfect motor-bearing-pump alignment.

Magnetic-coupled pumps (Fig. 2) are unique because they require no direct mechanical coupling of the motor to the pump impeller or shaft, and therefore no seals are needed, making them truly leakproof. The pump body is generally constructed of various plastics, and the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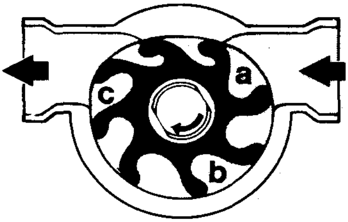
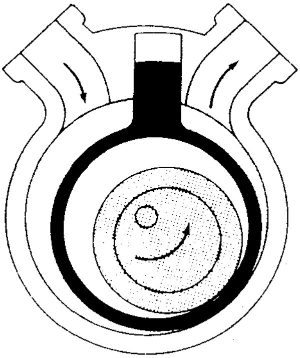


Fig. 3. Flexible impeller pumps utilize an elastomeric impeller that pushes the liquid from the inlet to the outlet port.

Fig. 4. Flexible linear pumps utilize an elastomeric liner that has an eccentric cam turning within it. As this rotates, it pushes the liquid from the inlet to the outlet port.



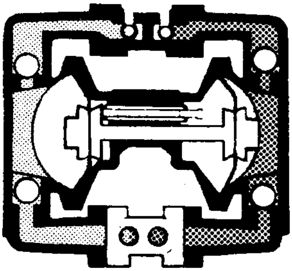


Fig. 5. Air-operated diaphragm pumps utilize air pressure acting on a manifold valve to provide alternate reciprocating motion to opposed diaphragms. When one diaphragm is pushing liquid out, the opposite diaphragm is pulling liquid in.

impeller magnets are encapsulated in plastic to eliminate any metal contact with the solution. Those without internal carbon bearings are used for electroless solutions. Magnetic pumps are also available with encapsulated motors, so that the entire unit may be submerged in the liquid. This is an extremely desirable feature for use in precious metal plating, to avoid loss of expensive plating solutions.

To efficiently provide a self-priming feature, close tolerances or actual rubbing must occur on both impeller and/or moving parts on the body of the pump. Most noteworthy is the fact that the greatest amount of wear occurs when the pump is developing its greatest amount of pressure as the plating filter is approaching maximum reduction of flow due to dirt pickup. Therefore, oversizing the filter will reduce the frequency of this occurrence. The flexible impeller (Fig. 3) and the liner impeller (Fig. 4) are both self-priming. They develop pressures up to 20 psi but require relatively frequent impeller or liner replacement when used continuously. Also, they cannot be used on abrasive solutions or where dry-running capability is required.

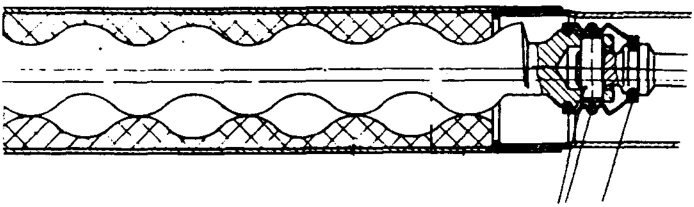


Fig. 6. Progressive cavity pumps. As one cavity formed by the offset helix diminishes, the opposite cavity increases. The result is constant, uniform flow over the length and out the discharge port.

Air-operated diaphragm pumps (Fig. 5) do not have rotating seals, impellers, or other internal parts. They depend on a pulsing, intermittent reciprocating motion acting on an elastomeric membrane to form a liquid chamber between two check valves and thus produce low flow rates at high pressure. The air supply can be regulated to produce certain performance requirements. Because of their self-priming feature, capability to run dry, and ability to handle extremely viscous liquids or materials with a high solids content, they are widely used in waste treatment and in other industrial applications. However, since these pumps pulsate, the filter and piping require pulsation dampening.

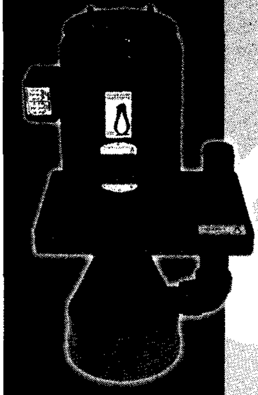
Another common self-priming pump design is the progressive cavity design (Fig. 6). This design uses a rotor, which has a helix turning inside a stator with a similar helix at a set pitch. Liquid is passed from one chamber to another along the length of the rotor. These pumps are well suited for high-pressure, low-flow conditions on either low- or high-viscosity liquids.

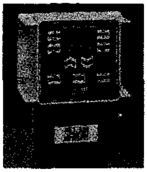
Horizontal centrifugal pumps not normally thought of as self-priming can be made self-priming by the addition of a priming chamber to the suction or discharge sides (or both) of the pump. Once the chamber is filled with liquid and the fill port securely sealed, suction lifts of up to 25 ft (depending on individual pump characteristics) may be achieved. Some pumps are capable of only a few feet of suction lift when a priming chamber is used. Basket strainers are available for priming chambers to prevent large solids from damaging pump internals.

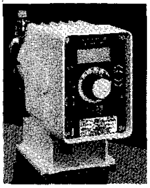
CENTRIFUGAL PUMP PRIMING

Priming of centrifugal pumps can be made easier if the following precautions are taken. Avoid all sharp bends or crimps in the suction hose. Prevent small parts from entering or restricting flow to the suction hose. Prevent air from getting into the pump by checking for poorly connected hose or flanged fittings, which may have vibrated loose. The slightest amount of air coming from an insufficiently tight threaded fitting or a loose flanged fitting prevents successful priming. Fittings with an "O" ring provide for a positive seal. As the pump packing wears, it will also suck air and, depending on usage, must be adjusted as required. (See tips on pump packing and the use of water lubrication to prevent sucking air.)

If frequent venting of the filter chamber is necessary when the filter is running, it is likely that an air leak has developed some place at the previously described two locations, and sooner or later priming will become more difficult. Air in the filter chamber is also an indication that the suction from the tank may be too close to an air outlet being used for solution agitation. A pump discharge fitted with a set of eductors could eliminate the problems associated with air agitation. Remember, the larger the pump, the more velocity is created and the more tendency to pull air into the suction opening. Priming is made easier with a slurry tank or priming chamber above the pump, making it possible to always have a flooded







suction. Recirculating through the pump, filter, and slurry tank and then slowly opening the line to the plating tank gradually purges the system of air. The suction valve from the plating tank should initially be opened only a crack, so that the pump does not get a slug of air at one time. This air also collects in the filter chamber and must be released by venting. In a precoated filter, any constant collection and venting of air soon results in ineffective filtration. As air collects, the cake falls away and is redeposited elsewhere. Subsequent venting returns solution to the unprecoated surface, where there is no filtering action, and the contaminated solution passes through.

To prime a centrifugal pump, if a hose is used on the suction side of the pump (without a slurry tank), liquid may be introduced through the hose and pump into the filter chamber. The filter need not be filled completely, but most contain a sufficient volume of liquid so that, as the hose is lowered to approximately the same height as liquid in the chamber, the hose will gradually fill with solution. Shake the hose to make certain any air trapped in the top of the pump or in other high points is completely expelled. When the liquid level completely fills the hose, keep the tip of the hose at the same position, but close the valve between the pump and the filter chamber. Now insert the hose in the tank (since the valve is closed, virtually no liquid will run out of the hose if a gloved hand is cupped over the end). Start the motor and wait until the motor has reached its proper speed; then slowly open the valve to the filter. This is a further precaution, which will enable the pump to create enough suction to handle the small amount of air that may still be in the line.

When transfer pumping out a tank, it is advisable to connect a 90° hose barb or a strainer to the suction end of the hose so that it may be lowered as solution level drops. This prevents cavitating the pump, which could occur if the end of the hose rested flat on the bottom or against the side of the tank. If the hose has a tendency to curl, insert a length of straight, corrosion-resistant pipe into the end to accomplish the preceding purpose. Since the most difficult time to prime a pump is after most of the solution has been removed from the tank, operators often dump this remaining heel, which is a needless waste of solution. Plating tanks with sumps at one end minimize this loss when solution transfer is necessary. Small self-priming pumps, such as drum pumps, may be used to salvage the heel left in the plating or treatment tank.

PUMP SEALS

The available types of pump seals vary from no seal at all to lip type, packed stuffing box, and mechanical. Since conventional pumps have an interconnecting shaft between the pump impeller and the motor, a suitable seal is necessary to prevent leakage during the rotation of this shaft. A magnetically driven impeller or vertical cantilever are perhaps the only truly seal-less pumps. Other pumps, which use a liner, or section of hose, are seal-less; but, since these components may fail through usage, fatigue, and abrasive wear, the system, like any other, is subject to eventual leakage. It is always desirable to replace seal components before leakage occurs. Unfortunately, one never knows just how much longer a seal will last before replacement is necessary. They may operate from a few minutes to a more realistic several years.

A lip-type seal consists of a molded, rubberlike material, which has a squeegee action in snugging itself around the shaft. A mechanical seal consists of two mirrorlike lapped surfaces, one rotating with the shaft, the other stationary in the pump, which are held together by a light spring pressure, preventing leakage. The preferred arrangement is an outboard mounted seal, so that exotic or nonmetallic seals are eliminated. A packing stuffing box consists of a suitable cavity, with the rotating shaft in the center, around which a compressible-type material may be inserted in alternating rings and held in place and adjusted by tightening the packing gland. Both the mechanical seal and the stuffing box seal are available with provision for water lubrication or recirculation of the solution being pumped. Usually, water from an external pressure water line is desirable, because it assures cooling and lubrication of the seal

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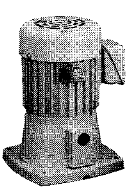

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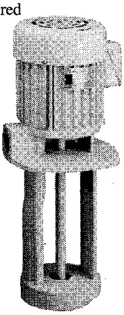

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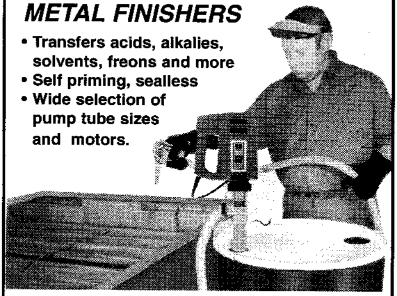

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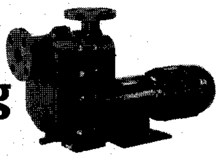

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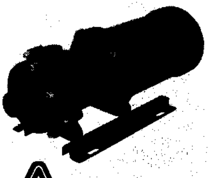

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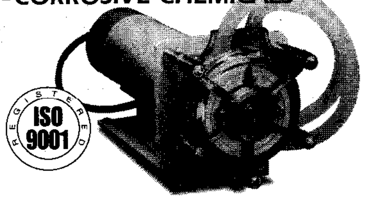

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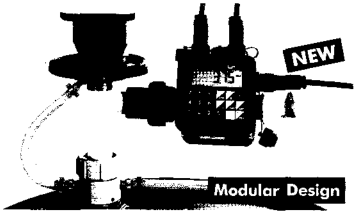

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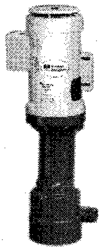

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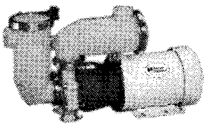

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components. It reduces wear by keeping filter aid and dirt out of the seal area. The water also prevents the solution from crystallizing on the seal faces during shutdown periods. Even while the pump is running, crystals may form as plate-out might occur with electroless solutions.

On double-seal pumps, care must be taken through the use of a check valve, or siphon breaker, so that no solution is pumped into the water system during an unexpected failure. Also, a regulator should be installed in the water line to control the pressure, because it will vary from low when the plating room is in operation to high during the weekend when no other water is being used. If the water pressure and flow to the seal are not regulated, it is possible to actually draw water through the packing into the plating tank, especially when the filter is clean, because a negative pressure exists at this point. This could cause chemical imbalance and even overflow of the plating tank. Solutions requiring deionized water for the seal use a double-seal arrangement, with an additional small pump recirculating the deionized water in the seal area.

When selecting the type of seal to use, consider the fact that a stuffing box seal or lip-type seal wears slowly, giving warning that replacement will be necessary by gradually increasing constant leakage. A mechanical seal is more trouble-free on a day-to-day basis and yet may fail without warning; thus, there is a need for preventive maintenance. (See piping instructions to minimize solution loss.)

Certain types of packing are more suitable for acid, and others are more suitable for alkaline solutions. The construction materials in a mechanical seal, such as the type of carbon and ceramic, along with what type of elastomer, also vary. Therefore, it is important to give the type of service to the manufacturer to assure suitable materials of construction. Some seal wear has to be expected, and periodic replacement of components is necessary. Whenever replacing the seal or packing, the pump shaft should be inspected. If worn or scored, it must be replaced.

SOLUTION AGITATION AND MIXING

by Ted Mooney

Finishing Technology, Brick, N.J.

In a few cases, solution agitation is employed with the intent of causing a mechanical scouring action. For example, in a spray washer, the cleaning fluid is caused to impinge forcefully on the work for this purpose. Similarly, in ultrasonic cleaning tanks, the cavitation created by the transducer is intended to induce a scrubbing of the surface of the work. In an electrocleaning tank, again, the gas liberated at the work surface fulfills the same objective. In electroplating processes, very high-energy agitation has been found to discourage formation of metal whiskers and to increase deposit hardness by promoting dislocations.

These examples of agitation, however, are the exceptions to the rule. In the metal-finishing theater, the normal role of solution agitation is a simple one—just another in a long list of requirements that must be met if we are to ask the real physical world to give credence to our man-made theories. That is, our calculations of plating rates and efficiencies, rinse ratios, and required reaction times, are invariably based, for simplicity's sake, on the supposition of solution homogeneity.

All we ask of an agitation system is that it generate sufficient mixing action that this supposition not be found presumptuous and wanting. But as in all real-world situations, things aren't as simple as they first appear.

HOW MUCH IS ENOUGH?

One doesn't generally describe the degree of agitation in superlative terms; it is neither outstanding nor abysmal, rather it is adequate or inadequate. But adequate cannot be interpreted except in context.

On the one hand, a hard-chrome plater may find that a daily hoeing-up of the bottom sludge in the plating tank ensures that the catalyst remains soluble in the proper proportion; for this plater, this constitutes adequate agitation. At the other extreme, a researcher knows that one can never totally negate the brake on theoretically possible plating speed, which is imposed by polarization and boundary layer phenomena; for the researcher, no combination of violent solution impingement, ultrasonic vibration, and pulsed current is ever sufficient to bring homogeneity all the way down to the microscopic level.

Between these extremes, the typical metal finisher may require that the agitation system assure general solution uniformity as well as provide enough turbulence to prevent excessive ion depletion or gas accumulation at the anode and cathode surfaces. In a pollution control system, the plater wants the agitators to provide sufficient mixing so that the reagent chemicals become intimate and react with each other, rather than pass placidly by each other as ships in the night.

THE BAD WITH THE GOOD

A complication with agitation systems is that they sometimes introduce extraneous factors and bring new problems.

The ubiquitous air agitation system can turn the process tank into an effective scrubbing system for concentrating the airborne dirt collected by the blower; it can cause roughness by stirring up bottom sludge; and it will oxidize the solution, which often will prove to be deleterious.

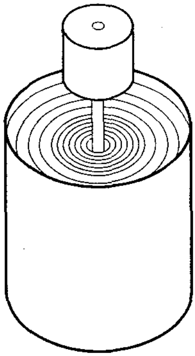

Fig. 1. Rapid solution movement, but minimal mixing.

The work movement developed by a cathode rocker can cause interrupted current and consequent laminar plating; in extreme cases, it can cause the work rack to walk out of its proper position.

Propeller-type mixers, commonly used in pollution control reaction tanks, can dice up the precipitated floc and impede its settleability/filterability. Circulation pumps can, through cavitation, wreak havoc by volatilizing solution components.

Despite these potential problems, agitation is usually a requirement—and a surfeit more generally acceptable than a shortage.

AGITATION VERSUS MIXING

Another complicating factor is the troublesome word agitation itself, because it implies a need for violent solution movement, whereas the usual actual requirement is for proper mixing—and the two are not necessarily congruent.

To clarify this, consider a cylindrical tank with a centrally mounted paddle-type mixer as shown in Fig. 1. Such a system might be employed in diluting a reagent, or in a pollution control reactor, or for batch carbon treatment of a nickel solution. The mixer will cause the contents to swirl rapidly, but actual mixing will be minimal (to appreciate this assertion, think about the fact that each droplet of solution is following an essentially fixed orbit around the mixer shaft). Actions taken to disrupt this orbiting, including installing baffles or moving the mixer off center, will cause the mixer's power to be absorbed in the desired shearing action rather than being available to rotate the contents as a whole, with the result that the solution may appear to the casual observer as less agitated.

Another example of movement, but little mixing, can occur with the typical rotating plating barrel illustrated in Fig. 2. There may be much agitation both within and outside of the barrel envelope, but little mixing through the envelope. Again, whether or not the mixing is sufficient depends on the particular requirements. Typically, the barrel rotation provides sufficient solution interchange to allow the plating process to proceed satisfactorily; but, conversely, rinsing will be improved if the barrel is momentarily lifted out of the rinse tank (allowing it to drain and refill) instead of being left immersed.

In deciding how to agitate a particular solution, the principal factors to consider include how much agitation is actually required, and what side effects are foreseeable.

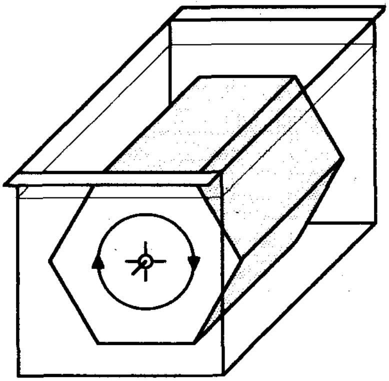

Fig. 2. Good mixing within barrel, but little between the inside and the outside.

AGITATION METHODS

There are countless casual forms of agitation: manual paddling, convection currents from heating and cooling coils, the disturbances caused by barrel rotation and movement of work in the tank, the solution motion resulting from the use of a filter pump, the mixing induced by the evolution of hydrogen at the cathodes, and so on. But in terms of practical engineered systems, we can restrict the discussion to air agitation, cathode oscillation, propeller type mixers, and circulation pumps—with a caveat that ultrasonic transducers and pulse plating rectifiers, each covered elsewhere in this *Guidebook*, are also actually agitation units in their own right.

AIR AGITATION

If air is forced to the bottom of a liquid-filled tank, and allowed to exit through a perforated pipe, the resulting bubbles will rapidly expand and race toward the liquid surface. Figure 3 conveys the general idea.

Air agitation has its undesirable facets. It will stir up bottom sludges and anode sludges, which, if not properly filtered, will cause roughness in the plating. It can cause excess foaming. It is poorly suited as a substitute for a mixer because powdered and low-density chemicals will tend to float on the surface rather than being drawn down into the mixing zone. It is rarely applied in pollution control operations because of its tendency to cause flotation of the precipitates. Thoughtless design or improper maintenance can mean that the air conveys inordinate volumes of oil and atmospheric dust into the process tank. Further, by its nature, the air will provide an oxidizing potential; while acid zinc baths might profit from this through oxidation and precipitation of iron, air agitation is never used in acid tin baths because the tin itself would oxidize, and rarely in cyanide solutions where it promotes formation of troublesome carbonates.

These limitations notwithstanding, air agitation is sufficiently simple, inexpensive, efficient, and generally applicable that it is probably the most common method of producing agitation in the metal-finishing shop today.

Air Sparger Design

The perforated pipe can be made of any material compatible with the solution and temperature involved, PVC being most common. The usual design calls for holes on about 4-

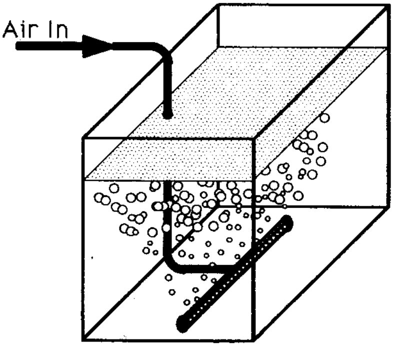

Fig. 3. Air-agitation concept.

to 6-in. staggered centers as shown in Fig. 4; the specified hole size is usually ³⁄₃₂ to ⅛ in., since smaller holes may plug too easily. An alternative to the traditional hand-drilled spargers is the newer porous pipe designs, which can save a lot of fabrication effort.

In order to promote even distribution of air along the sparger, it is important that it be installed in a level plane and that the cross-sectional area of the pipe be larger than the combined area of the holes. Pipe sizes as small as ½-in. diameter may meet this latter criteria, but for most production-size installations, it makes sense to use a minimum pipe size of 1 in. for mechanical rigidity.

General solution homogeneity is virtually assured with even a single air sparger, so rarely is more than one used in a rinse tank; however, preventing ion depletion or gas accumulation at the cathode of a plating tank may require multiple lanes of air spargers for full coverage, since the air tends to rise almost straight vertically and a single air pipe is usually credited with delivering only a 6-in. wide swath of generous local agitation.

Plastic pipes charged with air will have enough buoyancy to float, so they must be secured to the tank bottom or equipped with plastisol-coated metal weights. It is often recommended that the air pipes be positioned well off the bottom of the tank to minimize disturbance of accumulated sludges, but in reality the pipes are invariably set directly at the tank bottom.

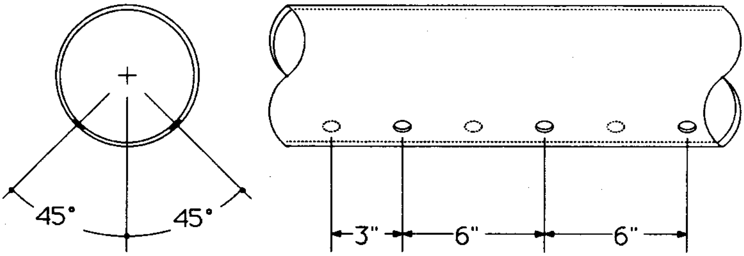

Fig. 4. Typical drilling of air-agitation sparger.

To preclude the possibility of solution siphoning out of the tank when the air supply is shut down, a small hole should be drilled in the riser, an inch or so above the solution level.

Air Blower Sizing and Selection

The air blower size is specified in terms of its output capacity in cubic foot of air per minute (cfm) and the back pressure against which it pumps. A good rule of thumb for initial calculations is to plan on providing 1 to 2 cfm for each foot of sparger pipe.

Back pressure is sometimes expressed in inches H_2O. Because two things cannot occupy the same space at the same time, to propel air to the bottom of a tank requires, in turn, lifting the column of liquid that stands above it up and out of the way. Thus, pumping air down to the bottom of a 48-in. deep water tank requires a static pressure of 48 in. H_2O (equivalent to 27.7 oz/in^2); but, because many of the liquids to be agitated weigh more than water, and because there are dynamic pressure losses associated with the pumping, for a first-cut approximation the back pressure can be estimated at an ounce per inch (48 oz/in^2 for a 48-in. deep tank).

The use of a conventional air compressor to supply the air is discouraged because of the high probability of introducing oil into the agitated tanks. Further, the cfm versus back-pressure ratings of air compressors align poorly with the usual requirements for agitation air.

For large installations, with a resulting need for copious volumes of air, a multistage turbine blower may be a good match. For most small to average size installations, the cfm versus back pressure needed is usually in a range not particularly well suited to traditional fans, turbine blowers, or compressors; in recent years, however, the development of the regenerative blower has filled this niche quite well.

In installing a blower, the need for filtration of the air cannot be overemphasized; read instructions carefully regarding proper filter types. Also double check the vendor's suggested method for adjusting air flow rates (for some blowers it is imperative that the outlet not be throttled but that, instead, excess air be dumped).

CATHODE ROCKER OSCILLATION

To obtain the requisite relative motion between work and solution, it is generally easier and more efficient to move the work than the solution. Thus, cathode rocker agitation is very widely used in printed circuit board (PCB) manufacture, nickel and precious metal plating, and wherever air agitation is undesirable.

The work movement can be vertical, horizontal, or a combination of the two. In many cases, the direction of motion is inconsequential; in other cases, for example in PCBs with plated-through holes, motion in one particular plane can be far more effective in propelling fresh solution to the point of interest than movement in the perpendicular planes.

For small tanks, the simple single-rod system shown in Fig. 5 is an off-the-shelf accessory that provides horizontal agitation. If vertical agitation is desired, it can often best be implemented with a see-saw arrangement that will minimize energy consumption and wear and tear, such as is shown in Fig. 6.

Whichever plane of oscillation is chosen, care should be taken in selecting and mounting the components to ensure that grease from the rocker will not leak into the tank, and conversely that racks lifted out of the tank will not drip corrosive chemicals onto the rocker system. In trying to provide for long service life, simple rollers of Teflon or polyethylene riding on stainless steel axles can be expected to endure the plating room environment more successfully than even the finest metal bearings.

The speed and stroke will vary depending on the application, but 15 to 40 cycles per minute with a stroke length of 2 to 6 in. covers the great majority of cases. Smooth motion suffices to prevent localized ion depletion with minimal risk of contact breaks, but a trip-hammer effect is especially well suited for dislodging troublesome gas bubbles in electroless plating operations.

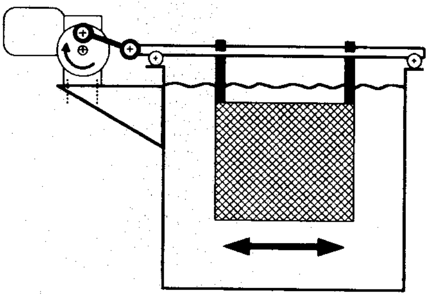

Fig. 5. Horizontal oscillation.

For large installations and where the work is to be oscillated in several tanks, it is possible to fabricate a ladder-shaped framework, such as is shown in Fig. 7, to sit atop the tanks and move all the workloads in tandem. This approach is widely implemented in production plating of printed circuits. The ladder must have sufficient integrity that the oscillatory energy is not lost to structural flexure. Again, plastic bearings and corrosion resistant construction should be used.

PROPELLER MIXERS

Although rarely used directly in plating operations, propeller mixers have individual applications at which they excel. A propeller mixer generates a vortex, which pulls material

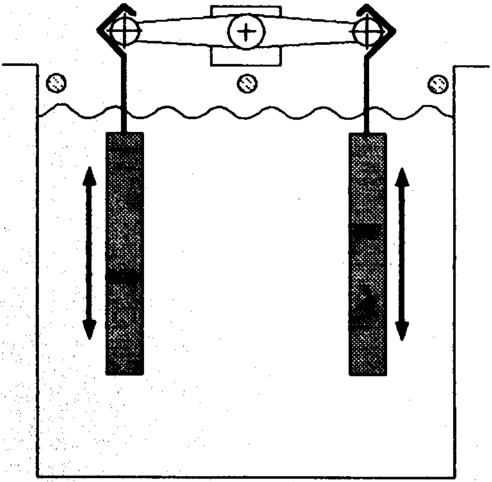

Fig. 6. Vertical oscillation.

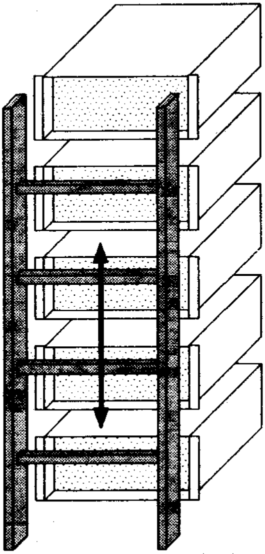

Fig. 7. Horizontal ladder oscillation.

down from the liquid surface and blends it into the body of solution; none of the other agitation methods has this capability, so none are as efficient at mixing dissimilar or reluctant constituents.

Propeller mixers are at home in blending operations, making up stock solutions, batch carbon treatments, and in pollution control reactors.

Direct-drive designs (1,800 rpm) are fine for most operations, but in critical pollution control installations, the extra cost of gear reducers to achieve slower speeds and avoid mutilating the floc, which would hamper its settleability, is usually justified. The gear drive mixers will utilize larger propellers so that they impart the same blending power into the solution but with lower blade tip speeds.

The mixer sizing is based on the volume of solution and how thorough a blending action is required; but the required size hinges so heavily on the viscosity of the solution that to include abbreviated selection charts here might do more harm than good. Detailed selection charts, as well as guidelines for maximizing the blending action, are available from the manufacturers.

For simple mixing needs, portable agitators are sometimes equipped with flat paddlelike blades in lieu of propellers. These units may be fine for the easy mixing jobs, but they cannot generate the whirlpool that is needed to pull buoyant constituents down into the mixing zone.

CIRCULATION PUMPS

Circulation pumps can be used for agitation and mixing, typically by laying the discharge pipe of the recirculation system along the bottom of the tank in the same fashion as an air agitation pipe, perforating it with holes on periodic centers, and pumping the recirculating solution through it. The majority of the pump's energy is lost to turbulence right at the pipe/solution interface, so this approach has not been very popular.

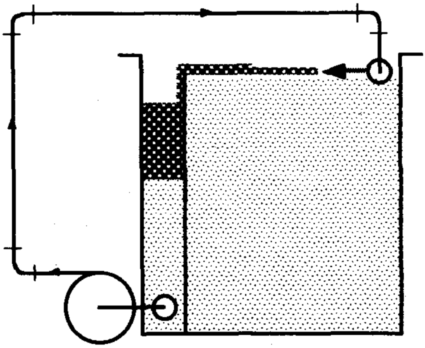

Fig. 8. Grease skimmer.

The recent development of engineered eductor systems, however, is rapidly changing this situation. In this approach, an eductor is mounted at each of the discharge holes to improve the mixing efficiency greatly. The pump propels the primary solution through a nozzle, but the nozzle is mounted inside a venturi bell, which induces a large secondary stream to flow laminarly through the bell as well. The result is efficient mixing.

Eductor systems can often deliver benefits similar to air agitation systems, while not drawing in dirty shop air, nor aerating or oxidizing the solution.

Pumps are also commonly employed with other aims in mind, and in meeting their primary objectives, they may serve to mix and agitate the solution. For example, circulation pumps that are installed to skim away floating grease on cleaning tanks will deliver solution agitation as a side benefit (see Fig. 8).

On systems employing circulation pumps, care should be exercised in limiting the amount of process solution that is at risk of being lost to drain in the event of a malfunction or improper valve setting. Also, caution should be used to ensure that safety is not compromised; the pump shown in Fig. 8 must be low pressure and the holes in the skimmer pipe must be large lest partial blockage raise the possibility of squirting alkaline cleaning solution at an operator.

CONCLUSIONS

Engineered agitation systems are indispensable in most metal-finishing shops. But agitating the solution invariably affects the process to one degree or another, so care must be exercised in the application.

IMMERSION HEATER DESIGN

by Tom Richards

Process Technology, Mentor, Ohio

The immersion heater represents a sound, economical method of heating process solutions in the finishing industry.

Classical heater installations consisted of hanging a steam coil on one tank wall, sized to heat up water to a "rule-of-thumb" temperature in two hours. While this method has proved adequate in providing heat and covering a multitude of oversights, it has also proved unsatisfactory with regard to energy costs and control. As the cost of energy rose, the finisher increased heat-up times in an attempt to conserve energy. Soon, heat losses prevented achieving desired temperature levels so tank insulation, covers, and other methods of loss conservation were added. Again, adequate solutions to most of the challenges were found, but the hanging steam coil remained unchanged. Today, we have the knowledge that allows us to adequately plan, design, install, and operate economical, efficient heating systems.

Molecular activity, chemical solubility, and surface activity are enhanced through temperature elevation. The reduced solution surface tension, low vapor pressure of some organic addition agents, and heat-sensitive decomposition or crystallization of other additives are major considerations that modify the benefits gained as solution temperature rises. To achieve a proper balance of all these factors, while providing economical installation and operation, it is necessary to analyze the individual heating requirements of each process. Your best source of process information is your process chemical supplier, which can tell you:

1. Recommended materials of construction.
2. Maximum (minimum) solution temperature.
3. Maximum heater surface temperature.
4. Specific heat of the process solution.
5. Specific gravity of the process solution.
6. Recommended heel (sludge) allowance.

To size the heater, first determine the tank size: space required for the part, parts rack or barrel, space required for busing (anodes), in-tank pumps and filtration, sumps, overflow dams, level controls, air or solution agitation pipes, and any other accessories. From this data, a tank size and configuration can be determined.

Calculate the weight of solution to be heated. For rectangular tanks:

$$\text{Weight} = L \times W \times D \times \text{S.G.} \times 62.4\ \text{lb/ft}^3$$

where L, W, and D are length, width, and depth in feet (substitute 0.036 lb/in.^3 for dimensions in inches). S.G. is the specific gravity of the solution (water is 1.0). For cylindrical tanks:

$$\text{Weight} = \text{R2D} \times \text{S.G.} \times 62.4\ \text{lb/ft}^3$$

where R is the radius of the tank.

Calculate the temperature rise required by subtracting the average (or lowest) ambient temperature from the desired operating temperature (if the shop temperature is kept very cool during winter months, it might be wise to use this temperature as the average ambient temperature).

$$\text{Temperature rise} = \text{T operating minus T ambient } [\text{To} - \text{Ta} = \text{T rise}]$$

Determine an adequate heat-up time to suit your production requirements. The traditional 2-hour heatup may prove costly and unnecessary since using this value usually provides a heater more than twice the size necessary for heat maintenance. A 4- to 6-hour heatup more

Table I. Heat Losses from Liquid Surfaces

Solution Temperature (°F)	*Nonventilated Losses (BTU/hr/ft²)*	*Ventilated Losses (BTU/hr/ft²)*
100	170	290
120	340	560
140	615	995
160	990	1,600
180	1,590	2,750

closely approximates the heat maintenance value but may impose production constraints deemed impractical. Long heat-up times can be overcome through the use of 24-hr timers; however, unattended heat-starts carry the responsibility of tank liquid level monitoring and approved overtemperature safety shutoffs.

With this data, the initial tank heating requirements can be determined. A BTU is the amount of heat required to raise one pound of water one degree Fahrenheit. A BTUH is that amount per hour.

$$\text{Initial BTUH(Q)} = \text{Weight} \times \text{T rise} \times \text{s.h./Heat-up time}$$

where s.h. is specific heat. This should be the actual value from the process supplier (water is 1.0).

Calculate the approximate heat loss from the tank surface and tank walls. (Use the data shown in Tables I and II.)

The losses from the tank surface can represent the most significant loss affecting heater sizing. The addition of even a partial or loose-fitting cover will reduce these losses. The tank surface area is simply the width in feet times the length in feet. You can use inches instead of feet, but then must divide the results by 144 to obtain square feet.

If you install partial covers, such as removable covers extending from the tank edge to the anode busing, use the remaining "open" dimensions. The covered area uses the reduced loss values shown in Table III. The use of partial covers reduces exhaust volume requirements and associated energy demands as well.

Air agitation can be said to primarily affect losses from the tank surface. Breaking bubbles increase the surface area and expose a thin film of solution to accelerate evaporative losses. Air agitation spargers sized at one cfm per foot of length affect a 6 in. (½ ft) wide path along their length. Thus, a three foot by four foot tank surface with two lanes of air agitation running on the four foot dimension has:

$$3 \times 4 = 12\ \text{ft}^2 \text{ surface plus } 2 \times \tfrac{1}{2} \times 4 = 4\ \text{ft}^2 \text{ agitation increase, a total } 16\ \text{ft}^2 \text{ effective}$$

Multiply the effective area by the values shown in Table I. Be sure to deduct any cover area (if used) and use the reduced loss values shown in Table III.

Table II. Heat Losses from Tank Walls and Bottoms

Solution Temperature (°F)	*Metal Tank or Thin Plastic (BTU/hr/ft²)*	*Insulated Tank or Heavy Plastic (BTU/hr/ft²)*
100	30	10
120	90	30
140	140	45
160	190	45
180	240	80

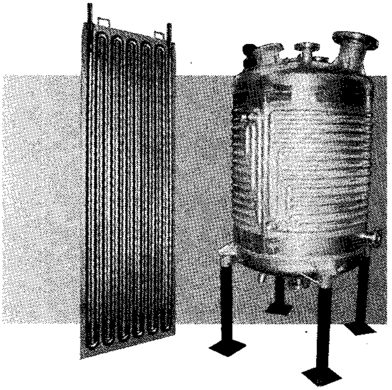

Table III. Cover Loss Values (BTU/hr/ft²)

Cover Style	*Still Air*	*Ventilated (150 fpm)*
Loose or partials	Metal tank values shown in Table II	Twice that for still air
Insulated	Insulated tank values shown in Table II	Same as still air
Floating balls	0.25 times the value obtained from Table I	Twice that for still air

The tank wall area equals the tank length in feet, times the depth of solution in feet, times two plus the tank width in feet, times the depth of solution in feet, times two plus the tank length in feet, times the tank width in feet. L × D × 2 + W × D × 2 + L × W = wall area. (You can use inches instead of feet but you must divide the result by 144 to convert into square feet.) Multiply the tank wall area times the values shown in Table II.

Calculate the heat loss through parts being immersed. Racks per hour, times the weight of the loaded racks, times the specific heat of the parts (use 0.1 for most metals, 0.2 for aluminum), times the temperature rise (use the same value used in calculating the tank temperature rise).

racks/hr × weight/rack × s.h. × T rise

A plastic or metal plating barrel must be included with the parts weight. A metal barrel has a specific heat value close to the average parts (0.1), and can be included in the parts weight, but a plastic barrel has a specific heat of 0.46 and will require an independent calculation. Weight of barrel, times barrel loads per hour, times the specific heat of the barrel, times the temperature rise.

barrels/hr × weight/barrel × 0.46 × T rise

Add to this the parts per barrel

barrels/hr × weight of parts/barrel × s.h. × T rise

The heat loading and the actual heat-up time for immersed parts are distinct values. The heated solution can lose temperature to the immersed parts in a matter of seconds. This heat loss is replaced by the heater. To determine the temperature drop of the process solution, divide the heat loss through parts (barrels) being immersed by the weight, times the specific heat of the solution.

Heat loss (parts)/[Weight (solution) × s.h. (solution)] = Temperature drop

Calculate the heat loss through solution additions such as drag-in and make-up water when working on small process tanks with high operating temperatures. In some operations, it is customary to replenish evaporative losses by rinsing parts over the tank. This practice increases the heat loading. Gallons of water each hour (drag-in or add), times 8.33 (lb/gal), times the temperature rise (water temperature to tank operating temperature).

gallons per hour × 8.33 × T rise

Now determine total heating requirement by comparing initial heat-up requirements with the sum of the various losses. Assuming no additions or operating losses during the initial heatup, we can equate our heater size based on the initial heat-up requirement, plus the tank surface losses, plus the tank wall losses. This value must be compared with the operating requirements—tank surface losses, plus the tank wall losses, plus the rack (barrel) losses, plus the drag-in (make-up) losses. The larger value becomes the design basis for heater sizing.

Heater sizing can proceed based on the heating method employed. Electric immersion heaters are sized based on 3.412 BTUH per watt-hour (3,412 BTUH per kilowatt-hour). Divide the design heating requirement by 3,412 to find kilowatts of electric heat required.

design heating requirements (BTUH)/3,412

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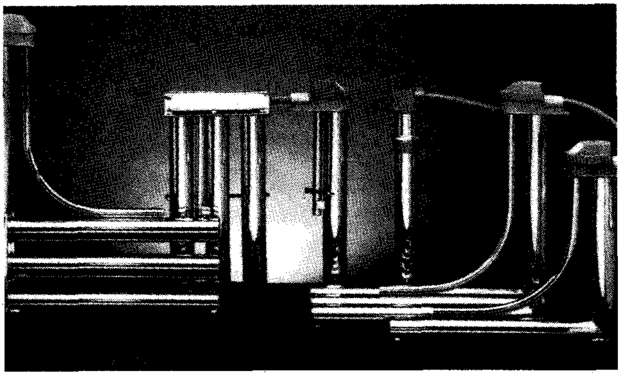

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The immersion heater sheath temperature will be higher than the solution temperature. Consult your immersion heater supplier for its recommendations where solutions have high temperature limits. Electric heaters have the potential of achieving sheath temperatures, particularly in air, and are capable of igniting flammable materials; therefore, it is essential that liquid level switches and high sheath temperature cutoffs be employed. Look for (or ask about) Underwriters Laboratory or other independent agency listing labels on electric heaters for assurance that the product meets a recognized standard. Verify and install the sheath ground to minimize personnel shock hazard and, as with all heaters, use a quality temperature controller for economical operation.

Steam immersion heaters are sized based on steam pressure, overall transfer coefficients, area, and log mean temperature difference.

The overall transfer coefficient is a value determined by several basic values: the ability of the heater material to conduct heat, the ability of the two fluid films that form on the inside and outside of the heater to conduct heat, and the resistance to the flow of heat caused by fouling or buildup. You can significantly alter the performance of immersion heaters by the choice of materials and the supply or the lack of supply of tank agitation. By selecting proper materials the fouling caused by corrosion is either reduced or eliminated. Clean quality steam will reduce internal fouling while properly placed agitation can enhance overall thermal performance. The precise calculation of the overall transfer coefficient is detailed and will not be covered here, but is available from your heater supplier.

The following rule-of-thumb values can be used for estimating steam heater size. For metal coils, the range of values for the overall heat transfer coefficient is 100–200 BTU/hr/ft^2/°F. For plastic coils, the overall heat transfer coefficient ranges from 20–50. Use 150 for metal and 40 for Teflon.

Now calculate the log mean temperature difference (LMTD) because the driving force for the heat exchange is a varying quantity that is expressed as this value.

$$\text{LMTD} = (\Delta T_1 - \Delta T_2)/[\ln(\Delta T_1/\Delta T_2)]$$

where ln = Naperian (natural) logarithms.

Steam pressure produces specific temperatures that will be used in the calculation of the LMTD. Typical values are given in Table IV.

As an example, assume 10 psig steam is to be used to heat a solution from 65°F (ambient shop temperature) to 140°F (solution operating temperature).

Steam temperature (from Table IV): 240°F

$$\Delta T1 = 240 - 65 = 175°\text{F}$$

$$\Delta T2 = 240 - 140 = 100°\text{F}$$

$$\text{LMTD} = (175 - 200)/[\ln\ (175/100)] = 75/0.55 = 134°\text{F}$$

The heater area required to steam heat a process solution equals the design heating requirement, divided by the overall heat transfer coefficient, times the log mean temperature.

$$\text{Design heating requirement (BTUH)/Overall heating requirement} \times \text{LMTD}$$

As with any immersion heater, the heater surface temperature will be higher than the solution temperature. Obviously, it cannot exceed the steam temperature. If the solution has a high temperature limit below available steam temperatures, you may require a custom electric immersion heater or a hot water (or thermal fluid) heater with a lower heating temperature.

Although the heater temperature is limited to the steam temperature, damage to process tanks and accessories can result from overtemperature or low liquid levels. It is wise to equip your process tank with overtemperature and low liquid level cutoffs.

Once a coil size is selected, piping size should be investigated. The quantity of steam used for a specific coil size varies with the steam pressure (see Table V) and the heat released

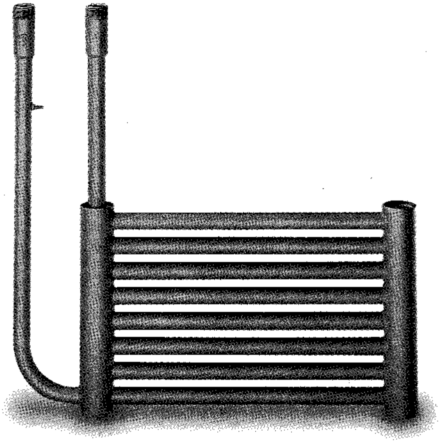

Table IV. Steam Table

Steam pressure (psig)	5	10	15	20	25	30
Steam temperature (°F)	226	240	250	260	266	274
Heat of evaporation (BTU/lb)	960	950	945	940	935	930

is the heat of evaporation (latent heat) only. The values in the table are in BTUs per pound of steam. So the quantity of steam required equals the design heating requirement, divided by the heat of evaporation of the steam.

Design heating requirement (BTUH)/Heat of evaporation (from Table IV)

The result, in pounds of steam per hour, can be equated to pipe size as shown in Table V. The condensate generated (condensed steam) must be "trapped," that is, equipped with a steam trap. Steam traps are sized based on pounds per hour times a safety factor. Since the amount of condensate varies with the temperature of the solution, it is wise to use a safety factor of four or better. Trap capacity equals the steam required times four.

The condensate piping is smaller than the steam pipe since the condensate is liquid. Some of the condensate will convert back to steam because of condensate temperature and pressure. The use of piping smaller than ½ in. nominal is not recommended since scale and buildup inside the pipe is a factor in all steam lines. We recommend using ¾ in. nominal pipe for condensate lines. This size will handle up to 1,920 lb/hr with a modest pressure drop.

Steam coil valve sizing is usually smaller than the pipe size since a pressure drop across the valve is required for proper operation. Some typical sizes for diaphragm solenoid valves are shown in Table VI.

Since the performance of the valve and trap can be affected by foreign matter in the steam, it is wise to place a 100-mesh strainer of the same pipe size as the steam pipe ahead of the valve.

Metal steam heaters, when suspended in electrified tanks, may conduct current through the steam lines to ground so it is a good practice to install nonconductive couplings between the heater and the pipe lines. This can be accomplished using a proprietary insulating coupling, dielectric union, or section of steam hose.

Finally, because some steam heaters may be buoyant (tend to float) when in service, it is necessary to secure these heaters through the use of ballasts or proprietary hold-down fixtures.

Hot water (thermal fluid) heating is similar to steam heating in the methods used for sizing. The basic differences involve the usually lower heating solution temperatures and the lower performance, overall heat transfer coefficient of the heater. As in the case of steam heating, the overall transfer coefficient is subject to varying performance and its precise computation is beyond the scope of this presentation. The following rule-of-thumb values can be used for estimating hot water heater sizes. For metal, the overall heat transfer coefficient is 70–100 BTU/hr/ft^2/°F. For plastic, the range is 20–50. Use 95 for metal and 40 for Teflon.

The calculation of the LMTD uses the same equation but now the heating fluid temperature must change since it is yielding the fluid heat and not the evaporative heat

Table V. Nominal Pipe Size for Various Steam Requirements

Nominal Pipe Size (in.)	*Steam Required (lb/hr)*
1	Up to 100
1½	100–300
2	300–500
3	300–1,000

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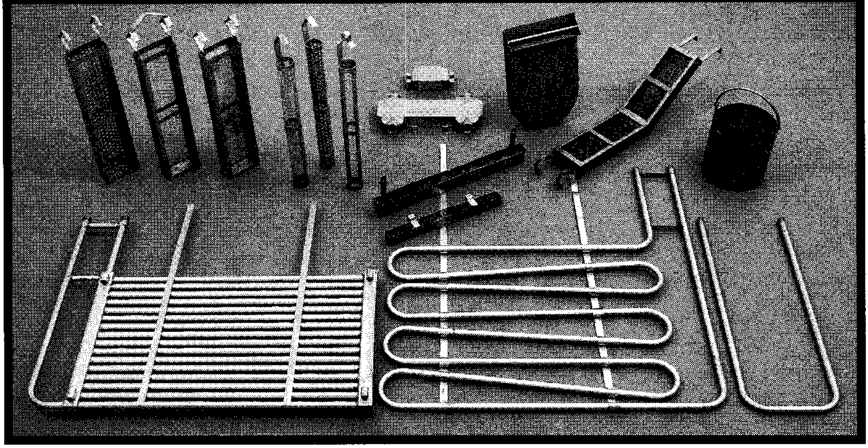

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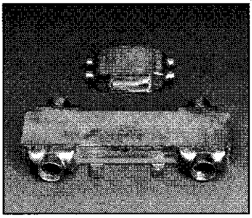

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Table VI. Recommended Valve Sizes

CV Factor	*Diaphragm Valve Pipe Size (in.)*	*Steam Required (lb/hr)*
4	1/2	120
5	3/4	150
13.5	1	400
15	1 1/4	450
22.5	1 1/2	675

available in steam. It is wise to limit the heat drop of the heating fluid to 10°F since greater drops may be impossible to achieve in a field-installed condition. Also, it is wise to design the exiting heating fluid temperature to be 15°F higher than the final solution temperature to ensure field reproduction of design performance. Consult your heater supplier for assistance if you experience any difficulty in sizing a heater.

As an example, heat a solution from 65°F (ambient shop temperature) to 140°F (operating temperature) using 195°F hot water. Limit the hot water temperature drop to 10°F or 185°F outlet. This temperature is more than 15°F above the final bath temperature.

$$\Delta T1 = 195 - 65 = 130°F$$

$$\Delta T2 = 185 - 140 = 45°F$$

$$\text{LMTD} = (130 - 45)/\ln(130/45)] = 95/1.0607 = 80.56°F$$

The heater area required to heat a process solution equals the design heating requirement divided by the overall heat transfer coefficient times the LMTD.

Design heating requirement/[Overall transfer coefficient × LMTD]

With hot water heaters, it is a wise precaution to install high liquid level cutoffs that will shut off hot fluid flow in the event of a heater leak. If a high temperature heating fluid is used, solution temperature sensitivity must be evaluated and high temperature, low liquid level cutoffs may be in order.

Once the coil area has been selected, the hot water (thermal fluid) flow must be calculated. The flow is equal to the design heating requirement, divided by the temperature drop of the heating fluid, times the specific heat of the heating fluid, times the specific gravity of the heating fluid.

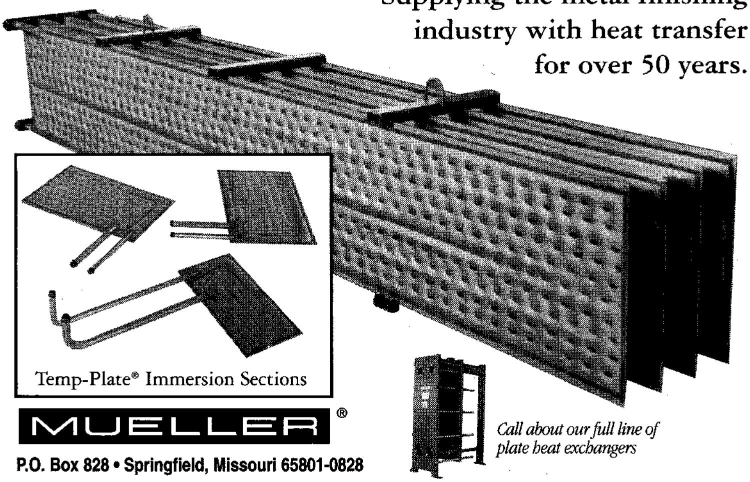
Design heating requirement/[Temperature drop × s.h. × s.g. (all of the heating fluid)]

This results in the pounds per hour of heating fluid. To convert this into gallons per minute, divide the pounds per hour by the weight of fluid per gallon times 60 (water weighs 8.33 lb/gal). This value is used to evaluate pipe size (both inlet and outlet). Table VII gives a reasonable flow for water through various pipe sizes.

The control valve may be smaller than the pipe size. Some typical sizes for diaphragm valves with a water pressure drop of 5 psig are given in Table VIII.

Table VII. Water Flow Rates for Various Nominal Pipe Sizes

Nominal Pipe Size (in.)	*Flow Rate (gal/min)*
1/2	6
3/4	10
1	20
1 1/4	30
1 1/2	45



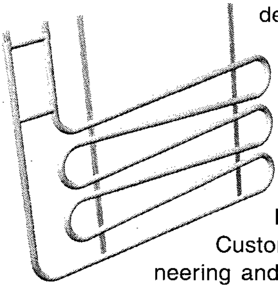


Table VIII. Typical Valve Sizes and Flow Rates for a Pressure Drop of 5 psig

CV Factor	*Diaphragm Valve Size (in.)*	*Flow Rate (gal/min)*
4.0	$\frac{1}{2}$	9
6.5	$\frac{3}{4}$	14
13.5	1	30
22.5	$1\frac{1}{2}$	50

As with steam heaters, it is a good practice to install a strainer to minimize foreign particles that may affect valve performance. A 60-mesh strainer is usually fine enough for hot fluid systems.

Metal heaters, when suspended in electrified tanks, may conduct current through supply lines to ground so it is a good practice to install nonconductive couplings between the heater and the pipe lines. A proprietary insulating coupling or dielectric union can be used.

Plastic heaters and some empty metal heaters may be buoyant, so be sure to provide adequate anchoring if floating is suspected.

Thermal stratification is a fact of life in heated process tanks. To minimize this effect good agitation (mixing) is required. Classic air agitation is sized at one cfm per foot of length. When placed beneath a cathode (or anode) it provides sufficient agitation to that surface to enhance deposition rates. It does not, in this form, eliminate thermal stratification. Top-down mixing can be provided through recirculation pumping. Pumps sized for 10 turnovers or more per hour provide good mixing and uniform temperatures. Skimming style pump inlets with sparger bottom discharges are best since higher temperature solutions are forced to the cooler areas.

In tanks three feet deep and more, a vertical sump pump can be mounted on the tank flange with a length of discharge pipe anchored to the tank bottom. These can often be coupled to in-tank filters for removal of particulates while providing mixing. Air agitation, when properly placed, can "average" temperature in their zone of influence (usually 6–12 in.) and can be used to enhance response time for temperature controller sensors. As the air agitation is increased, heat losses also increase, making air agitation a less desirable means of dealing with thermal stratification.

Heat sensitive solutions can be addressed by either electric or hot water (thermal fluid) heaters. Electric is the easiest to control since the heater surface temperature can be varied by varying the input voltage. A heater surface temperature controller can limit surface temperatures while still providing sufficient heat for the solution. Similarly, hot water systems can be sized for maximum hot water temperatures (and thus heater temperatures) but control and response are usually inferior to electric systems.

FLUOROPOLYMER HEAT EXCHANGERS

by S. R. Wharry, Jr.

Ametek/Haveg Div., Wilmington, Del.

Fluoropolymer heat exchangers are the only polymeric heat exchangers to offer the temperature capabilities and corrosion resistance necessary to heat and cool acid- and caustic-based plating baths. They offer economical solutions to the problems of maintaining precise temperature control of baths for optimum product quality.

INTRODUCTION

Polymeric heat exchanger usage has become widespread throughout today's industry for heat-transfer applications in highly corrosive situations. The principal reason that polymeric heat exchangers are used instead of conventional metal heat exchangers is that all metals are subject to corrosion in chemical media. Although the corrosion rate of certain metals may be acceptable in the chemical species utilized, they all suffer corrosion, and when aggressive chemical media are used, the rate of corrosion becomes prohibitive to economical operation.

There are many types of thermoplastic and other polymeric materials available in heat exchangers (polypropylene and polyethylene have been used for some very low-performance applications), but only a few polymers exhibit the chemical and temperature capabilities that make them suitable for widespread heat-exchanger application. In general, the polymers that exhibit these properties are the fluorocarbon family of resins. They are available from several different resin manufacturers and each exhibits a general range of acceptable usage.

FLUOROPOLYMER STRUCTURE AND PROPERTIES

The wide acceptance of fluoropolymer heat exchangers can primarily be attributed to the unique properties of the fluorocarbon polymers. Fluoropolymers are corrosion resistant to almost all chemicals, with the key to this corrosion lying in the chemical structure. Polytetrafluoroethylene (PTFE), perfluoroalkoxy (PFA), and fluorinated ethylene propylene (FEP) fluoropolymers are fully fluorinated polymers; that is, each branch terminates with a fluorine atom (see box). Polyvinylidene fluoride (PVDF), ethylene tetrafluorethylene (ETFE), and ethylene-chlorotrifluoroethylene (ECTFE) are only partially fluorinated (some branches do not end with a fluorine atom).

This fully fluorinated structure provides a polymer that is both chemically inert and thermally stable to high temperatures. Partially fluorinated polymers sacrifice some chemical and thermal resistance to enhance their mechanical properties at room temperature. This results in the higher ambient temperature tensile strength and modulus shown in Table I. As can clearly be seen, however, the upper operating limits of the PVDF, ETFE, and ECTFE are severely restricted and FEP and PFA have higher temperature limits. This is important in heating applications when thermal margins of safety can be extremely important. One can also readily see that the fully fluorinated structure of FEP and PFA (Table II) offers superior chemical resistance compared with the other partially fluorinated polymers. This is especially true in the area of strong alkalies, polar solvents, and strong acids.

Two fluoropolymer family members, EFTE and ECTFE, have to date found more applications in structural and lining applications and not in heat-exchanger equipment.

THERMAL PROPERTIES

Fluoropolymers are not good heat conductors. Shown in Table III is a tabulation of thermal conductivity values comparing the various fluoropolymers directly with those of

Table I. Properties of Fluorinated Polymers

Type		*PTFE*	*FEP*	*PFA*	*PVDF*	*ETFE*	*ECTFE*
Specific weight	g/cc	2.17	2.15	2.15	1.78	1.75	1.7
Melting point	°C	327	270	305	178	275	240
	°F	621	518	581	350	527	464
Tensile strength	mPa	30	20	31	54	24	31
	psi	4,350	2,900	4,500	7,830	3,480	4,500
Yield stress	mPa	10	12	15	46	24	31
	psi	1,450	1,740	2,250	6,670	3,480	4,500
Elongation	%	500	350	300	150	500	300
Elastic modulus	mPA	600	500	700	2,400	1,500	1,650
	psi $\times 10^3$	87	72	101	348	217	240
Shore D hardness		60	57	62	79	75	75
Impact strength		160	200				
{1200)	J/m						
ft-lb/in.^{2}		3			4		
Heat Distortion							
Temperature	°C	121	70	73	148	104	115
66 psi (0.46 mPA)	°F	250	150	164	300	219	240
Linear expansion							
coefficient	10^{-5}K	13	13	12	12	12	12
Thermal							
conductivity	BTU/hr/ft^2	0.23	0.20	0.22	0.19	0.23	0.15
	ft^2 -°F/in	1.6	1.4	1.5	1.3	1.6	1.0
Upper service							
temperature	°F	500	400	500	300	280	340
	°C	260	205	260	150	140	170

ECTFE; ethylene-chlorotrifluoroethylene; ETFE, ethylene tetrafluoroethylene; FEP, fluorinated ethylene propylene; PFA, perfluoroalkoxy; PTFE, polytetrafluoroethylene; PVDF, polyvinylidene fluoride.

metals. In light of these relatively poor thermal properties, why then does a fluoropolymer work as a practical heat exchanger? When dealing with a heat-transfer situation, one first determines the amount of heat necessary to be transferred. It is then simply a direct function of the heat-transfer coefficient or the capability of the heat exchanger, the area available for heat exchange, and the temperature driving force used to promote that heat transfer.

$$Q = UA\,\Delta T_L \tag{1}$$

Here, there is a log mean temperature difference, because in the dynamic situations occurring during tank heatup or cooling, there is a constantly changing system, not a constant temperature. The log mean temperature is defined by the following equation:

$$\Delta TL = \frac{(T_{2L}-T_{1L})-(T_{2F}-T_{1F})}{Ln\left[\dfrac{(T_{2L}-T_{1L})}{(T_{2F}-T_{1F})}\right]} \tag{2}$$

Note that it is not a simple temperature difference with which one must deal. The main consideration in this article, however, is calculation of the heat-transfer coefficient, as it develops from the relatively low thermal conductivity.

$$U = \frac{1}{\dfrac{1}{h_o}+\dfrac{1}{h_w}+\dfrac{1}{h_i}+f_o+f_i} \tag{3}$$

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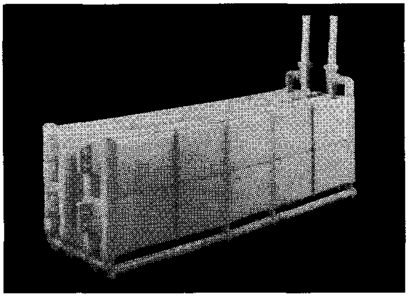

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Table II. Chemical Resistance of Fluoropolymer Resins

	PTFE			*FEP*			*PFA*			*PVDF*		
Media	*20°C*	*60°C*	*90°C*	*20°C*	*60°C*	*90°C*	*20°C*	*60°C*	*90°C*	*20°C*	*60°C*	*90°C*
H_2SO_4 (15%)	A	A	A	A	A	A	A	A	A	A	A	A
H_2SO_4 (98%)	A	A	A	A	A	A	A	A	A	A	A	A
HCl (36%)	A	A	A	A	A	A	A	A	A	A	A	A
HNO_3 (50%)	A	A	A	A	A	A	A	A	A	A	A	A
Nitric (20%)/HF (5%)	A	A	A	A	A	A	A	A	A	A	A	A
HF (40%)	A	A	A	A	A	A	A	A	A	A	A	A
Chromic (50%)	A	A	A	A	A	A	A	A	A	A	A	B
NaOH (50%)	A	A	A	A	A	A	A	A	A	B	B	U
NaOCl	A	A	A	A	A	A	A	A	A	B	B	U
Cl_2 (wet)	A	A	A	A	A	A	A	A	A	A	A	A
Ketones, esters	A	A	A	A	A	A	A	A	A	B	U	U
Aromatics	A	A	A	A	A	A	A	A	A	A	A	B
Chlorinated solvents	A	A	A	A	A	A	A	A	A	A	A	B

A, acceptable; B, conditionally acceptable; U, unsatisfactory.
FEP, fluorinated ethylene propylene; PFA, perfluoroalkoxy; PTFE,polytetrafluorethylene; PVDF, polyvinylidene fluoride.

Table III. Coefficients of Thermal Conductivity

	Thermal Conductivity	
Material	*BTU/hr ft²-°F/in.*	*W/M°K*
Copper	2,700	390
Graphite	830	120
Nickel	619	89
Tantalum	368	50
Carbon steel	348	50
Titanium	111	16
Stainless steel	104	15
Ni-Cr-Mo	56	8
PTFE	1.6	0.23
PFA	1.5	0.22
FEP	1.4	0.20
PVDF	1.3	0.19

FEP, fluorinated ethylene propylene; PFA, perfluoroalkoxy; PTFE, polytetrafluoroethylene; PVDF, polyvinylidene fluoride.

In this simple definition of the heat-transfer coefficient (Eq. 3), the individual film coefficients are summed up; i.e., what happens to the fluid outside the tube in the bath (h_o), conduction of heat through the wall (h_w), transfer of heat between the fluid in the tubes to the wall (h_i), plus fouling factors. This summation yields the overall coefficient or U value, which is a measure of the ability of a heat exchanger to transfer heat.

Taking the example shown here and applying typical data, film coefficients for inside the tubing (condensing steam 500 BTU/hr/ft²°F or greater) and in the surrounding bath (200 to 300 for agitated systems) can be inserted. Typical textbook fouling factors are 0.001. If small-diameter tubing is considered, typically ⅛-in. diameter tubing with a 0.00125- in. wall (discussion of this typical value is later in the text), the conductivity calculates to a coefficient of 96 BTU/hr/ft²°F.

$$U = \frac{1}{\dfrac{1}{500} + \dfrac{1}{96} + \dfrac{1}{300} + 0.001 + 0.001} = 57.8 \tag{4}$$

Plugging all of these values into the equation for the overall heat-transfer coefficient (Eq. 4), it is obvious that the most significant and controlling factor in this calculation is the wall of the tubing. The order of magnitude of this resistance is greater than that in the fluids on either side, and especially so for the fouling factors. For this reason, when sizing any fluoropolymer heat exchanger, fouling factors are not considered to be an important item. Since the order of magnitude is so small, compared with the controlling factor, it becomes mathematically insignificant. The nonstick character of fluoropolymers further enhances the logic that fouling factors are not important.

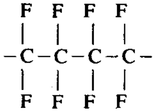
This U value of approximately 60 is typical for steam heating in a plating bath with pure fluoropolymer tubing. The wall conductivity of a metal heat exchanger (based on thermal conductivity is approximately 75 times that of the fluoropolymer heat exchanger) results in an overall heat-transfer coefficient typically three times that of the fluoropolymer heat exchanger. If the mathematics as shown in Equation 5 are reviewed, it can be seen that the order of magnitude of the fouling factors is very significant for a metal heat exchanger, and, therefore, must always be considered when calculating necessary heat-transfer area.

$$U = \frac{1}{\dfrac{1}{500} + \dfrac{1}{1500} + \dfrac{1}{300} + 0.001 + 0.001} = 150 \tag{5}$$

Approximately 4 years ago, a fluoropolymer tubing called "Q" tubing was introduced. It effectively doubled the thermal conductivity over that of all pure fluoropolymers available. If that wall conductivity number is doubled to approximately 200 BTU/hr/ft^2°F, the wall is still the controlling factor, but now you have closed the gap considerably with metals (Eq. 6).

FLUOROPOLYMER STRUCTURES AND PROPERTIES

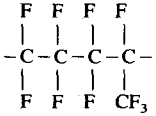
PTFE-Polytetrafluoroethylene:



$$-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-$$

Melting Point 620°F (327°C)
Service Temperature 500°F (260°C)
Chemically inert
Insoluble

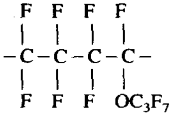
FEP-Fluorinated ethylene propylene:



$$-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{CF_3}{C}}-$$

Melting Point 540°F (280°C)
Service Temperature 400°F (205°C)
Chemically inert
Insoluble

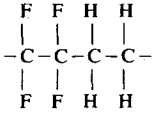
PFA-Perfluoroalkoxy:



$$-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{OC_3F_7}{C}}-$$

Melting Point 580°F (301°C)
Service Temperature 500°F (260°C)
Chemically inert
Insoluble

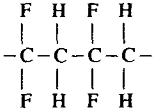
ETFE-Ethylene tetrafluoroethylene:



$$-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-$$

Melting Point 512°F (267°C)
Service Temperature 300°F (150°C)
Reacts-strong acids/bases
Insoluble

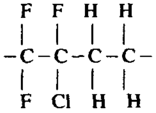
PVDF-Polyvinylidene fluoride:



$$-\overset{F}{\underset{F}{C}}-\overset{H}{\underset{H}{C}}-\overset{F}{\underset{F}{C}}-\overset{H}{\underset{H}{C}}-$$

Melting Point 320°F (160°C)
Service Temperature 280°F (140°C)
Reacts-strong acids/bases
Soluble in ketones

ECIFE-Ethylene-chlorotrifluoroethylene:



$$-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{Cl}{C}}-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-$$

Melting Point 465°F (240°C)
Service Temperature 340°F (170°C)
Good-acids/bases
Poor-organics & solvents

Table IV. Thermal Efficiency versus Tubing Diameter

Tubing Diameter (in.)	(mm)	Type	Wall Conductance Coefficient Kcal/hrM^2 = °C	BTU/hr/ft^2-°F/in.
0.100	2.54	FEP	586	120
0.100	2.54	Q	1,170	240
0.125	3.18	FEP	468	96
0.125	3.18	Q	928	190
0.175	4.45	FEP	336	69
0.175	4.45	Q	668	137
0.250	6.35	FEP	234	48
0.250	6.35	Q	468	96
0.3175	8.06	FEP	185	38
0.3175	8.06	Q	366	75
0.375	9.53	FEP	156	32
0.375	9.53	Q	322	64

FEP, fluorinated ethylene propylene; Q, a fluorpolymer tubing.

$$U = \frac{1}{\frac{1}{500} + \frac{1}{200} + \frac{1}{300} + 0.001 + 0.001} = 84 \qquad (6)$$

The coefficient now typically ranges up to 120 BTU/hr/ft^2°F against a typical metal heat-transfer coefficient range of the order of 150 to 300 BTU/hr/ft^{2}F. What one must do in a fluoropolymer heat exchanger to match the performance of a metal unit is, therefore, to specify more surface area; however, because of the generally smaller diameter of the tubing utilized in fluoropolymer heat exchangers, the surface area available per running foot or per cubic foot of heat exchanger is significantly higher than that of the metals; therefore, the unit, while it contains more surface area, does not occupy a higher volume and does not detract from available bath area.

FLUOROPOLYMER HEAT EXCHANGERS

Fluoropolymer heat exchangers are generally manufactured with small-diameter tubes. Functionally, it becomes very difficult to gain heat-transfer efficiency in tubing above ½-in. diameter. The wall thickness required to provide structural strength of tubing larger than that reduces the thermal efficiency considerably. Table IV shows the various sizes of tubing available in units in both FEP and Q.

The smaller diameters have significantly higher wall conductivity and, therefore, create a much more thermally efficient unit; however, the smaller diameter tubes are generally suitable only for clean fluids inside the tubes. One generally makes immersion units out of smaller diameter tubes where clean steam or cooling water flows in the tubes. Larger chemical process units are made out of the larger diameter tubes where dirty process fluids are introduced tubeside in the heat exchangers. Units of this latter type are also appropriate for external heaters/coolers for metal finishing baths.

Because tubing is extruded from fluoropolymer resins, pressure capability is a strong function of temperature. The pressure capabilities of the various fluoropolymer resins are very much regulated by the temperature of the application as well as the upper temperature capabilities of the various polymers (Fig. 1). Most manufacturers of fluoropolymer heat exchangers follow a similar pattern. Tubing is typically manufactured with what is called a 10% wall. In other words, the wall thickness is 10% of the diameter of the tubing. Some tubing can be made as low as 8% wall without serious effects on its pressure capability. With the use of the 10% rule for wall thickness, all tubing within this size range (less than ½ in.

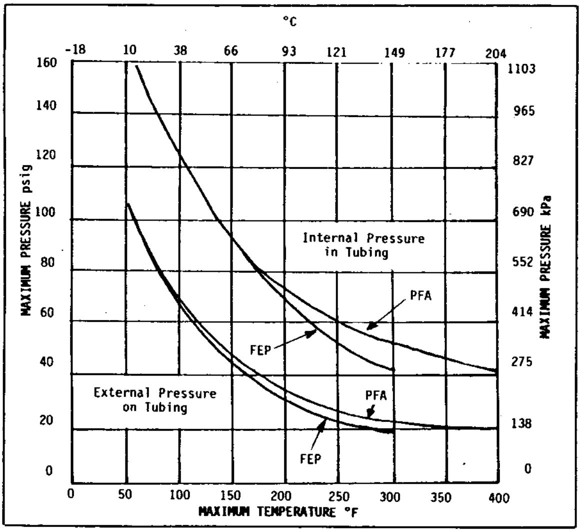


Fig. 1. Operating limits.

diameter) has generally similar temperature/pressure capabilities. Differences in tubing capability created by the hoop stresses in this size range are relatively insignificant and considered to be nonexistent.

COMMERCIAL USE

This discussion will focus on what can be broadly characterized as the metal finishing industry. Technically, all establishments that apply coatings or surface treatments to a metal item are part of the metal finishing industry. Many additional operations also fit into this general category, such as mechanical polishing, painting, and the application of other coating materials. These areas seldom require heat exchange and, as such, the involvement is limited to the plating and similar chemical or electrochemical finishing operations where corrosive solutions and heating or cooling are involved. Some categorizations of the type of operations included are:

- Decorative plating
- Hard chromium plating
- Precious metal plating
- Chloride, cyanide, fluoride, fluoborate, fluosilicate, pyrophosphate, sulfate, and sulfamate plating solutions for cadmium, chromium, copper, gold, lead-tin, nickel, platinum, rhodium, silver, tin, and zinc electroplating
- Electroless copper and nickel plating solutions
- Deionized water
- Anodizing, brightening, cleaning, electrocleaning, electropolishing, etching, neutralizing, passivating, pickling, rinsing, stripping, and surface-activating solutions containing alkalis or acetic, chromic, hydrochloric, hydrofluoric, nitric, oxalic, phosphoric, or sulfuric acids

Some of these applications are designed to provide decorative finishes to make the article more attractive. More importantly, they can provide functional finishes that impart specific

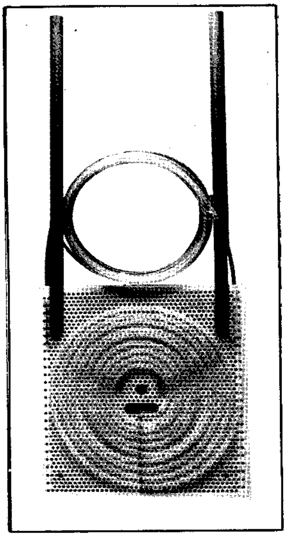


Fig. 2. Minicoil.

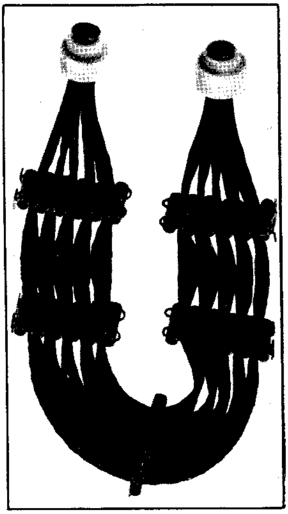


Fig. 3. Supercoil.

engineering properties such as surface hardness and resistance to wear, abrasion, or corrosion to the article being plated. In all of the above operations, precise control of bath temperature at an optimum condition is critical to obtaining a product of the highest quality.

Baths must be heated from room temperature to provide the optimum temperature for processing and then maintained at that condition, either through additional intermittent heating or by cooling, especially in the case of electroplating where the electric energy that is input into the bath is translated into significant heat values. Fluoropolymer heat exchangers can provide heating as well as cooling in a single unit. Electric or flame heating requires a second unit for cooling.

In today's metal finishing baths, heating and cooling with fluoropolymer heat exchangers can be accomplished in a number of ways. The first, and perhaps the simplest, technique is an immersion heater/cooler placed directly in the plating bath itself. Several types of these heat exchangers are available. The smallest of these units is a board- or frame-mounted unit available from several vendors (Fig. 2). They are most typically used in small plating baths, but through modular-type construction can provide significant area. They have the deficiency of being fabricated from ¼-in. or larger diameter tubing, which provides an inefficiency of operation because of the thicker walls. They also are of a single-tube design, requiring individual tube connections into manifolds for operation with the heating or fluid media. The single-tube design can also limit coolant flow.

The second category of immersion coil is that typified by the supercoil (Fig. 3) in sizes ranging from approximately 10 to 75 ft^2 in heat-transfer area. These are produced in both FEP and Q tubing utilizing ⅒- and ⅛-in. diameter tubing. These types of coils utilize a process called honeycombing, which fuses the many small-diameter tubing ends into a single fluorocarbon sheath (which is provided with a mechanical connection to a standard NPT Teflon or steel piping connection). In this way, a client can connect the coil utilizing standard supply piping and is not required to manifold many small tubes individually. Larger coils are

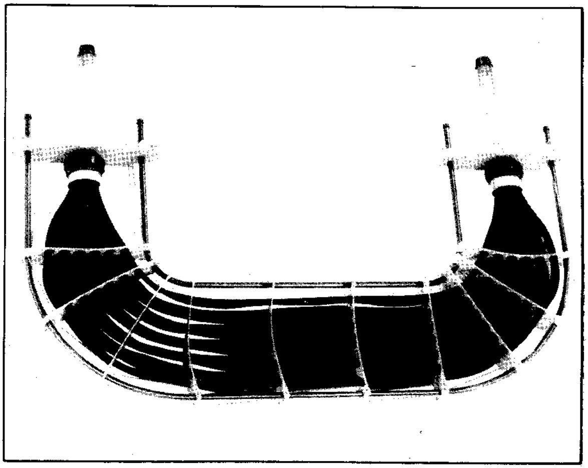


Fig. 4. Slimline.

also produced called slimline immersion coils (Fig. 4). These can provide up to 250 ft^2 in a single coil and are held in a rigid configuration by external Teflon-covered steel rods.

Of course, external tank heating is also a possibility and is utilized by many metal processors. This is simply utilization of a shell and tube unit with fluoropolymer tubes contained in a steel or noncorrosive shell for the heating/cooling media (Fig. 5). Detailed selection of materials can be made for the shell and sealing gaskets, depending upon the nature

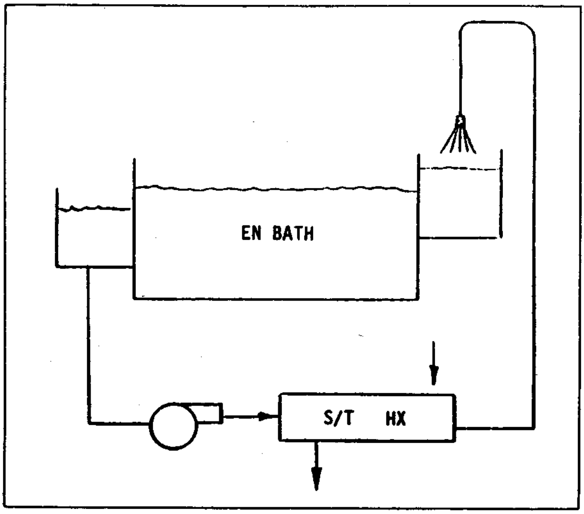


Fig. 5. External bath heating.

of the media involved. In shell and tube units, it is advisable to use slightly larger diameter tubing, as the bath solution is being circulated through the tubing of the heat exchanger, and particulate contamination as developed in the bath can be circulated through the unit.

ADVANTAGES OF FLUOROPOLYMER HEAT EXCHANGERS

Fluoropolymer heat exchangers are true heat exchangers. They are not heaters. They can be used for heating and cooling of corrosive bath environments. Following are some of the advantages compared with some of the competitive heating techniques.

- Fluoropolymer heat exchangers have near universal corrosion resistance. This results in long life, no plating bath contamination from corrosive products, and a smaller spares inventory because fluoropolymers work in all solutions, which provides extreme versatility. You can use the same heat exchangers even though the bath composition is changed.
- Fluoropolymer heat exchangers are electrically nonconductive. They are simple, easy to install, and electrically insulated pipe connections are not needed. You get improved plating efficiency because stray currents are not attracted to a nonconductive fluoropolymer heat exchanger. There is no shock hazard. Generally, operating costs are lower than with electric heat. There are no burned-out heaters, which need frequent replacement.
- Units are safer to operate as there is no risk of tank ignition or damage to tank lining if solution level drops. This compares not only to an electric heater situation, but also to nonelectric heat sources, such as flame or carbon "hot sticks."
- Fluoropolymers resist fouling and plateout. So, surface passivation may be eliminated in certain solutions.
- There is longer bath life, and less bath depletion as compared with direct steam or hot water injection. There is less waste for disposal or recovery.
- Original heat transfer performance is maintained. It does not deteriorate with plateout, as plateout is dramatically reduced.
- A single unit can be used to provide both heating and cooling in a single bath.
- They are easy to repair. Simple patching or elimination of a single tube can be done depending on the type of heat exchanger with no significant effect on thermal performance. No special welding techniques are required. Most repairs can be handled by plant maintenance people. There is no need to send it out to a special welding shop, which can require several weeks.
- They are compact and flexible. They can be installed out of the way, and shaped to fit into tank spaces. They are extremely cost effective when the total life and replacement cost of metal units are considered.

VENTILATION AND AIR POLLUTION CONTROL

by Arthur N. Mabbett

Mabbett & Associates Inc., Bedford, Mass.

The primary function of an industrial exhaust system is to protect workers against potentially toxic and irritating airborne contaminants generated in the workplace: contaminants from metal-finishing tanks are generally irritants to human tissue. Insufficient ventilation may be manifested by worker complaints or obvious eye, nose, or throat irritation upon entering the work environment. Air sampling may be necessary to evaluate exposure conditions where substances with poor warning properties are in use. Substances with poor warning properties are those that do not produce noticeable odor or irritation even at unacceptable levels. A properly functioning exhaust system will have the benefits of maintaining a safe comfortable work environment, as well as prolonging the life of corrosion-susceptible plan components and equipment.

New facilities should be designed to control these contaminants in the workplace through proper ventilation. Existing facilities should be evaluated for acceptability of the work environment. This article describes the basics of ventilation design and the use of air pollution control equipment to remove contaminants before discharge to the outside air.

CODE OF COMPLIANCE

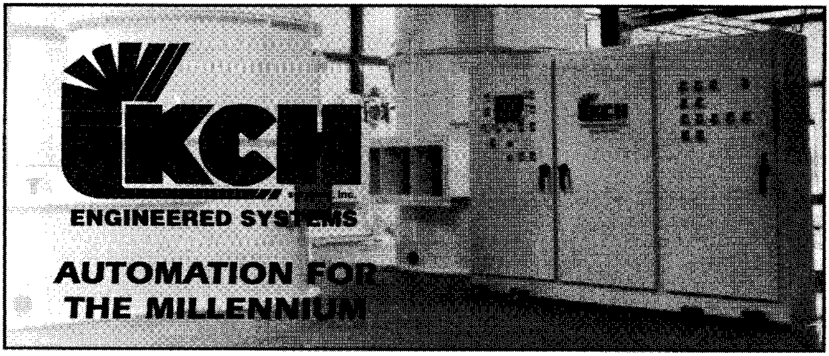
The quality of workroom air is regulated by the federal Occupational Safety and Health Administration (OSHA) and, to some extent, by state bureaus of occupational hygiene. Copies of applicable regulations should be obtained prior to initiating design activities.

Two generally accepted reference documents for designers are *Practices for Ventilation and Operation of Open Surface Tanks*, by the American National Standards Institute (ANSI) (Z91-1977), and *Industrial Ventilation: A Manual of Recommended Practices*, by the American Conference of Governmental Industrial Hygienists (ACGIH), Committee on Industrial Ventilation, Lansing, Mich. The Sheet Metal and Air Conditioning Contractors' National Association, Inc. (SMACNA), Chantilly, Va., has also published several manuals that are useful for specifying engineers and installers.

TYPES OF SYSTEMS

The two methods of handling contaminant exhaust are local exhaust ventilation and general dilution (Fig. 1). Local exhaust ventilation means controlling contamination at its source, whereas dilution ventilation means treating the workroom as if it were a "mixing box" or contamination sink. In general, dilution ventilation is not as effective for health hazard control as is local ventilation. Dilution ventilation requires greater air flows to achieve the same effect as local exhaust ventilation and cannot protect workers who must work close to the process operation.

Although there are occasional circumstances where dilution ventilation must be used because the operation or process cannot accommodate local exhaust, local exhaust ventilation is by far the most cost-effective and generally accepted method of contaminant control. Many plating and metal-finishing shops have a number of different open surface tank processes that require exhaust ventilation. The exhausts from most, if not all, of the process baths can usually be combined into a single exhaust system; however, segregation into multiple systems is desirable in certain situations.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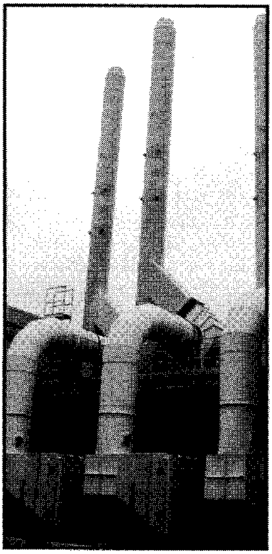
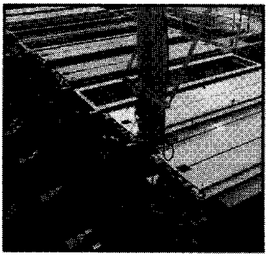
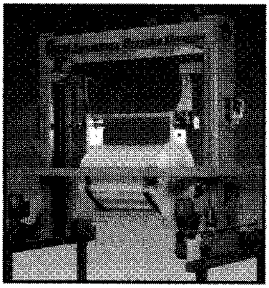
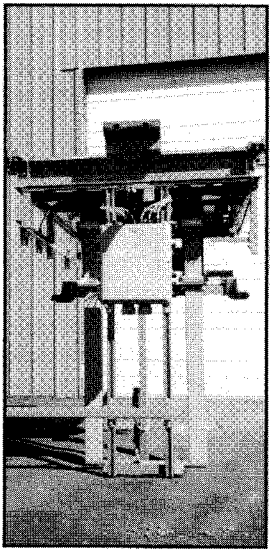








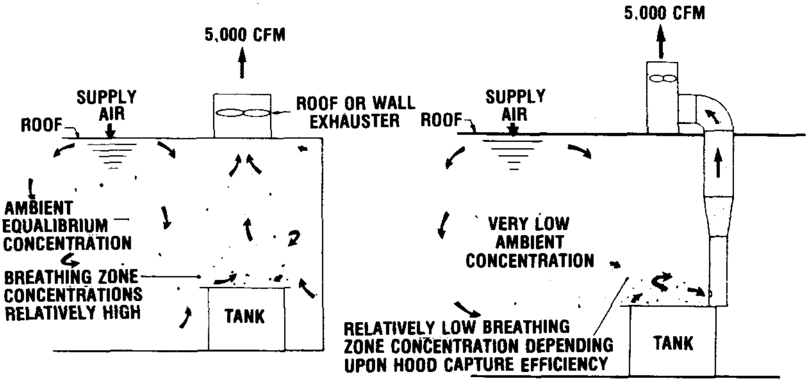


Figure 1. Left: general dilution ventilation—room behaves as a mixing chamber; right: local exhaust ventilation—localized capture provides lower room and breathing zone contaminant concentrations using the same amount of exhaust air as general dilution ventilation.

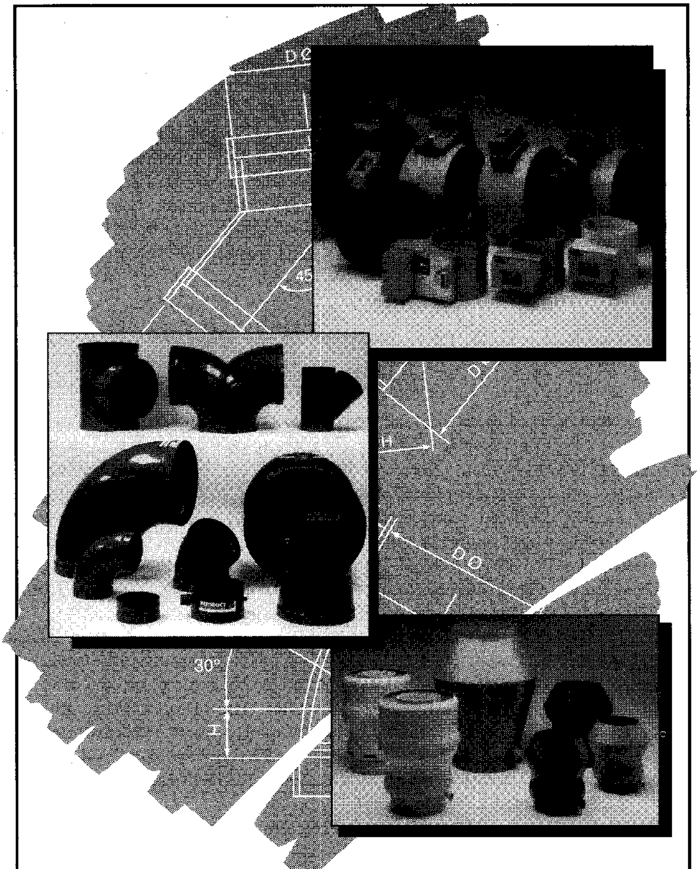
Layout or duct-sizing considerations may indicate the need for separate systems. If a process is infrequently used, a separate exhaust system, which can be turned off, will save energy. When both acid- and cyanide-containing solutions are to be vented, separate systems should be used, if practical, to prevent the possible formation of hydrogen cyanide gas. Similarly, ammonia- and chlorine-containing exhaust streams should be kept separate to prevent formation of ammonium chloride, a fine white particulate that will cause a visible plume, which is difficult for conventional air pollution control equipment to remove. Oxides of nitrogen (NO_x) from fuming nitric acid tanks present a particularly difficult emission-control problem. If strict control of NO_x emissions is indicated by plant siting considerations or by air-quality authorities, the NO_x exhaust stream should be kept separate to minimize treatment costs.

Generally, the advantages of separate systems are partially offset by the higher overall capital cost of air-moving and cleaning equipment, and by potential make-up air distribution control problem.

NATURE OF CONTAMINANTS

Not all finishing operations are identical in emissions of air contaminants. Air contaminants from open surface tanks vary in type, intensity, and toxicity depending upon the operation. All of these factors are significant in the determination of ventilation and air pollution control requirements for a facility.

The type of emission is very important when designing a ventilation system. There are two types of air contaminants from open surface tanks: mists and gases. typically, tanks containing water-based solutions emit mist droplets in the range of 0.5–50 μm in diameter, having the same chemical make-up as the tank. Gases and vapors, characterized as molecular forms having diameters <0.01 μm, are emitted from the evaporation of tank components; such emissions can include hydrogen cyanide, hydrogen fluoride, hydrogen chloride in water-based solutions, as well as solvents such as methanol, naphtha, or chlorinated hydrocarbons. These types of emissions can be captured using local ventilation. The distinction becomes important when considering effective capture by a local exhaust, transport in ductwork, and collection in air pollution control devices.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The rate of evolution of air contaminants will, in part, determine the ventilation requirements and is dependent on the type of finishing operation performed and on the specifics of an individual operation. Mists arise from the bursting of bubbles at the liquid surface, entraining tank components into the air. These bubbles can be caused by electrolysis, by nonelectrolytic chemical reactions with the work, and by physical actions such as air and mechanical agitation of the bath. Gaseous emissions can be affected by the same elements, as well as by temperature. In both cases, the rate of material processed is a major factor in emissions. Based on the rate of contaminant released by the tank, the rate of local exhaust is determined. Highly reactive metals or processes require high ventilation rates.

The most important factor in local exhaust is the toxicity of the air contaminant. Toxicity is specific to the chemical emitted. Maximum permissible exposure limits (PELs) are mandated by OSHA and guideline threshold limit values (TLVs) are recommended by the ACGIH. Acceptable levels in the air can range from 0.1 to 50 ppm and are based on available data concerning health effects of exposure to the compounds. A local exhaust and ventilation system is designed based on the allowable or recommended exposure levels.

These three factors, type, rate, and toxicity of contaminant release, are carefully considered when designing a local exhaust ventilation system. Data have been tabulated for each factor and, as is described in subsequent sections, ventilation systems can be designed from these compilations.

DESIGN

Exhaust system design begins with the individual exhaust hood. The intent of the exhaust hood is to sweep emissions from the tank surface, away from the workers' breathing zone, in the most energy-efficient manner. The amount of exhaust flow and, therefore, of energy required, depends on the particular plating or metal-finishing process and the degree to which it can be physically enclosed. Enclosure is desirable because it minimizes crossdraft interference and reduces the amount of open surface area to be controlled. It is best achieved with full or partial covers, or with booth-type arrangements over the tank surface. Surface enclosure is also partly achievable by floating spheres or surface tension chemical agents in the liquid.

Once a hood configuration has been selected, the next design step is to calculate the required exhaust flow. Exhaust flows are calculated based upon the individual processes and are dependent upon the type of contaminants to be controlled, the rate at which contaminants are evolved, the temperature, and the size of operations, among other factors. In general, exhaust flows should adequately control workroom air concentrations to within acceptable health levels. Potential corrosion of the workroom and workpieces is another concern. (Refer to the aforementioned documents for process specific ventilation rtes.)

Exhaust flows in excess of those required for health considerations may be necessary to control product quality. It should also be noted that OSHA mandates the use of standard tables for flow calculation if employee exposure to air contaminants is found by air sampling to be in excess of the PELs. (Refer to OSHA General Industry Standards, 29 CFR 1910.94[d] and 1910.1000.)

HOOD TYPES

The three basic hood designs are the lateral slot hood, the canopy hood, and the booth hood with one open side. The lateral and canopy types are most efficient when combined with baffles or curtains to approach the booth configuration having one open side.

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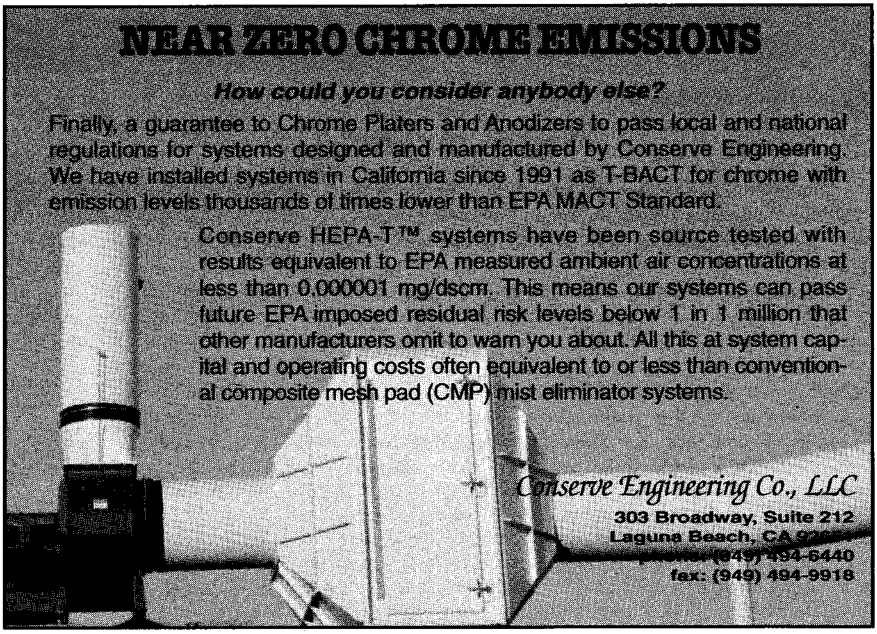

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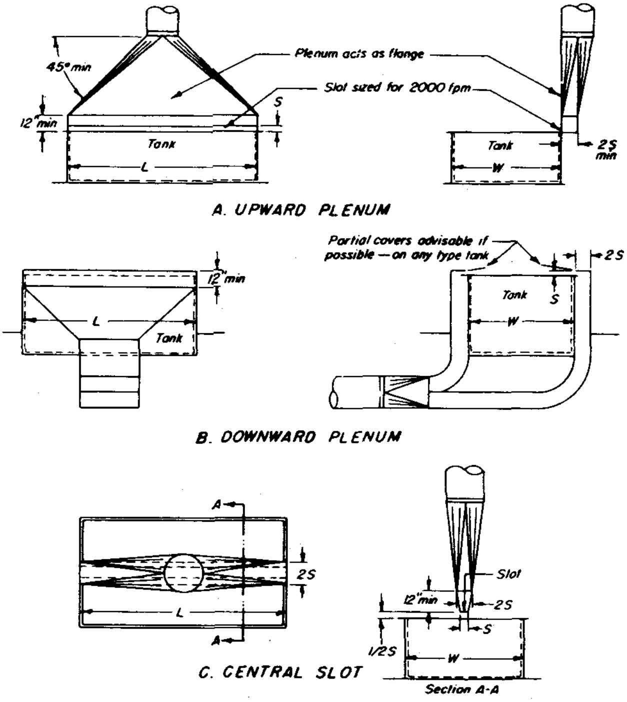


Figure 2. Lateral slot hoods.

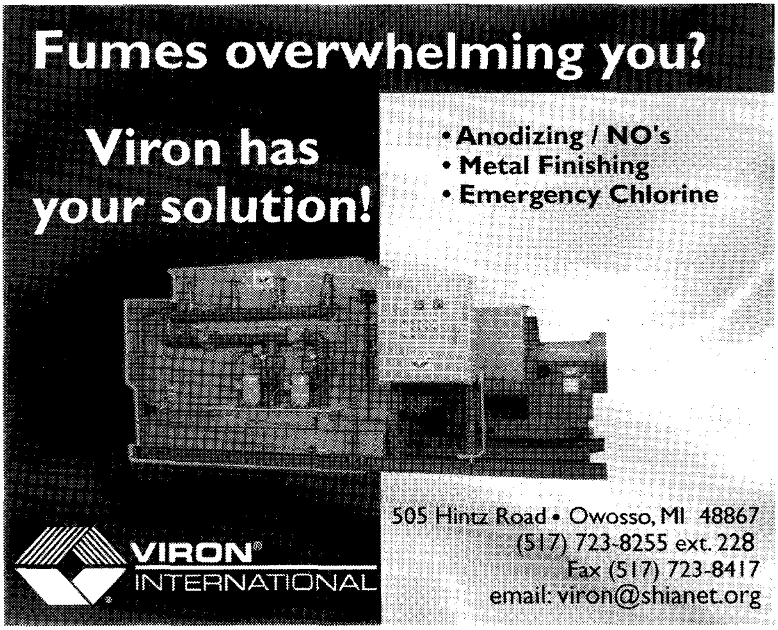
LATERAL EXHAUST

Lateral slot hoods are depicted in Fig. 2. Although lateral hoods have the potential for requiring the greatest amount of exhaust flow among the various hood types, they are the type most commonly installed because they create minimum physical interference with the process.

The slot entry must be sized to furnish a minimum-recommended entry velocity of 2,000 fpm. The recommended slot-entry velocity will ensure even distribution of flow across the slot opening. Slot velocity alone does not determine the control velocity achieved at the tank surface boundary: the slot's sole purpose is to distribute flow. The plenum behind the slot should have a depth at least twice the slot width to ensure distribution across the face.

Where the effective width (W) over which the hood must pull air to operate exceeds 20 in., slots on both sides are desirable. Where W exceeds 36 in., slots on both sides are necessary. If W exceeds 48 in., lateral exhaust is not usually practical unless enclosure or push–pull arrangements are used. Variations of the basic lateral slot hood are depicted in Fig. 2B and C. Slots on two or more sides of the tank provide more favorable aspect ratios, allowing the use of less exhaust air relative to a single slot.

Minimum-recommended flow rates are for tank locations with minimum crossdrafts, specifically crossdrafts <50 fpm. Lateral hoods are highly susceptible to crossdrafts caused by open windows or doors, particularly when make-up air is not mechanically furnished to the space. The distribution of make-up air to the workroom can also be a source of undue



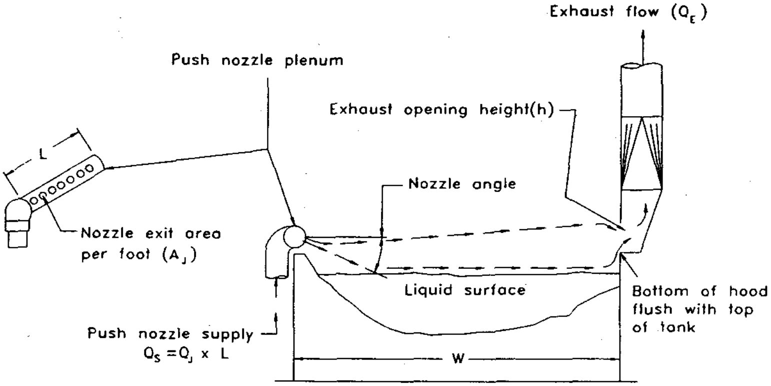


Figure 3. Push–pull exhaust hood.

turbulence. Increased exhaust flow, proportional to the increased magnitude of crossdraft velocity, is required to achieve the contaminant control necessary.

PUSH–PULL LATERAL EXHAUST

For large open surface tanks, normal lateral exhaust is not feasible due to the enormous amount of exhaust needed to maintain capture velocities at the far end of the tank. Instead, a push–pull-type exhaust, as depicted in Fig. 3, can be used. Push–pull exhaust combines a lateral slot hood at one end of the tank with a jet of push air at the opposite end. Push air is typically furnished by a dedicated supply fan located in the workroom: compressed air is an unnecessarily expensive source of push air.

Push–pull systems offer the potential advantage of achieving control with less exhaust air flow, particularly where crossdrafts are a problem, making exhaust of wide tanks more feasible. One recent study demonstrated a 97% contaminant capture efficiency for a 4 × 6-ft heated tank equipped with anode bars, where crossdrafts were 75 fpm. Push air was furnished through a ¼-in. slot at 35–45 cfm/ft of tank length, and exhaust flow was 50–75 cfm/ft^2 of tank area.

The design of push–pull systems is empirical, and such systems should be designed so that they can be easily modified or adjusted to obtain the desired results. The major drawback of push–pull systems is that obstructions, such as the work, anode bars, etc., may deflect the curtain of air and scatter it, along with air contaminants, into the work area; hence, the need for design flexibility.

Design criteria can be found in the latest edition of the ACGIH manual or other references.

OTHER EXHAUST HOODS

The canopy hood is a receiving-type hood and is most appropriate for hot processes where vertical convection currents move contaminants toward the hood. Canopy hoods work best when side curtains are furnished approaching the booth configuration. A canopy hood without curtains is not recommended for cold processes due to the ease with which crossdrafts divert contaminants away from the hood.

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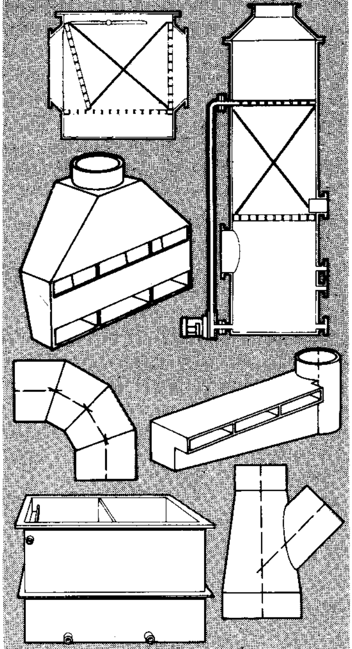

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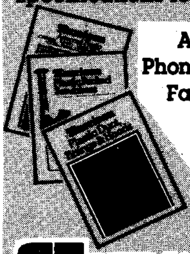

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Table I. Comparative Exhaust Flow Rates for Various Hood Types[a]

	Single Slot	*Lateral Exhaust Slots at Front and Back*	*Push–Pull*	*Open Canopy*	*Enclosing Booth*
Control velocity, fpm	100	100	—	175	175
Design velocity, fpm	175	150	100	—	—
Flow rate, cfm	2,190	1,875	1,250	8,135	750

[a]Single-slot fishtail-type hood. Lateral slots located at inside tank edge.
Double-slot fishtail-type hood on rear, downdraft on front.
Canopy hood located at 2 ft above process.
Enclosing booth with 2-ft high by 5-ft long opening on one side.
12½-ft^2 tank area.

COMPARING EXHAUST OPTIONS

For comparison purposes, Table I indicates the minimum-recommended exhaust flow for a 2½ × 5-ft alkaline cleaning tank operating at 200°F, for each of the hood types discussed. The table illustrates the differences of one hood type or another in required air flows.

DUCT SYSTEMS

Ducts are the link between the fan and hood to convey air contaminants. Industrial exhaust ducts are sized by the system designer to provide an air velocity that will keep air contaminants in suspension during transport to the scrubber fan, but which is not so great as to cause unnecessary friction losses and equipment strain. For gases and vapors, any transport velocity is acceptable; economic considerations result in a usual transport velocity of 1,000–1,500 fpm. For open surface tanks, and the contaminants generated, a duct velocity of 2,000–3,000 fpm is commonly recommended.

There are two general approaches to duct design, the "self-balanced system" and "blast gate" methods. With the self-balanced system approach, ducts are sized and flows are adjusted so that the minimum-desired hood flows are achieved without the use of balancing dampers or blast gates. With the blast gate method, system balancing is achieved using strategically placed blast gates, or blast gates at each hood. (The reader is directed to the ACGIH *Industrial Ventilation Manual* for details.) Each design has advantages and disadvantages. The self-balanced system has the advantage of being relatively tamperproof and of ensuring that design transport velocities are maintained. Flows cannot be altered without adjusting the fan speed or drive. The disadvantage is reduced flexibility because temporarily inactive hoods or branches cannot easily be shut off. Conversely, the blast gate method is subject to tampering, but offers greater operational flexibility. Accordingly, self-balanced systems are ideal for nonchanging processes and processes utilizing extremely hazardous components, where ventilation tampering is undesirable.

Prior to selecting a fan from the manufacturers' performance tables, the actual pressure losses must be obtained by calculation of duct, hood, and air acceleration losses, and by contacting air pollution control equipment manufacturers. Typical fan static pressures for open surface tank exhaust systems are 2-in. water column (WC) for systems without scrubbers, and 3–5 in. for systems with scrubbers. Slot hoods, designed as previously described, will produce a pressure drop ranging from approximately 0.5 to 1 in. WC. The typical duct system will add an additional 0.5–1 in. WC. Exhaust gas scrubbers have pressure drops typically ranging from 0.5 to 3 in. WC.

Smooth air flow is an important consideration for duct-system design to conserve energy. Good engineering fluid flow practices and general principles should be incorporated into the design and construction of a duct system. Flexible duct is commonly employed as an expediency, but its use should be minimized. Resistance to flow from flexible duct is substantially greater than that for smooth duct. This results in excessive fan horsepower for systems designed for flexible duct, or inadequate flow on systems not specifically designed for flexible duct.

Impaction of contaminant mists on duct surfaces invariably leads to buildup in the ductwork of liquids and solids left behind by evaporation of the liquids. Cleanouts should be furnished at specified intervals on straight horizontal runs and at each elbow. Ducts should be sloped to a low point and drains with traps or isolation valves should be furnished at this point.

The most cost-effective duct material will vary from installation to installation. Duct selection, and therefore cost, depends upon corrosion and temperature requirements, desired lifetime, and insurance underwriter requirements.

Several materials are commonly used for duct and hood construction. Manufacturers' tables of corrosion resistance should be consulted during selection of specific products. An excellent reference source of corrosion-resistant properties for numerous materials is the *Corrosion Data Survey*, metals and nonmetals sections, obtainable from the National Association of Corrosion Engineers, Houston, Texas. In general, duct service is less severe than the immersion ratings typically given in tables of corrosion resistance. Hoods and ductwork are typically constructed of galvanized, resin-coated or stainless steel, or plastics such as polypropylene, polyvinyl chloride (PVC), or fiberglass-reinforced plastic (FRP). The plastics are currently in widespread use because of their excellent corrosion-resistant properties.

A prime consideration in the selection of duct and hood materials is combustibility. Polypropylene, PVC, and FRP are all combustible to varying degrees. Fires originating in process tanks, typically caused by electric immersion heaters in dry tanks, are a fairly common occurrence. The tank fire spreads to the plastic hood, with the potential for involving the entire exhaust system and adjacent building components. Some insurance underwriters require plastic ductwork to be furnished with internal sprinklers, whereas others will accept the system without sprinklers provided that materials do not exceed a certain thickness, e.g., ¼-in. maximum thickness for PVC. The basis for the thickness exemption is that thin walls will melt more quickly and interrupt flame spread. The FRP duct is usually assigned a flame spread rating, with better ratings achieved by the addition of fire retardants to the resin. A few proprietary FRP duct systems, which incorporate patented flame interrupters and fire-retardant resins, have been approved for use without internal sprinklers.

Where higher temperatures may be encountered due to the process, or on rooftops in southern climates, temperature-rated FRP or steel construction may be preferable to plastics, which soften at elevated temperatures. Open surface tank exhaust systems draw in large amounts of room air, consequently the duct is typically exposed to temperatures of 100°F or less.

The relative cost of one material compared with others for a given duct system will depend upon the number and size of fittings, the availability of standard extruded or fabricated duct for the desired diameter, and the availability of qualified installers for specialty duct. Generally speaking, relative duct cost for an installed system is given in ascending order of cost as follows: plain steel, galvanized steel, resin-coated steel, PVC, polypropylene, FRP, proprietary flame-interrupting FRP, and stainless steel.

EXHAUST FAN TYPES

The energy required to induce a flow of air through a local exhaust system is provided by an exhaust fan. There are two basic types of fans to choose from, axial and centrifugal. Among the available materials of construction, PVC and FRP are more commonly used for exhaust fans handling the highly corrosive fumes that are produced in metal finishing.

Axial fans move air parallel to the fan shaft. The propeller type is commonly used to move air from one room to another or from outdoors to indoors. Vane axial and tube axial fans are both installed in ducts, with the main difference between them being the higher pressures achieved in vane axial fans (up to about 6 in. water gauge) due to their air guide vanes. The relatively low static pressures obtained by axial fans, as well as their low resistance to abrasive dusts, limit their usefulness as industrial process exhaust fans.

Centrifugal fans can be classified into three main types: forward curved blade, backward inclined (BI) blade, and radial blade.

A forward curved blade, or squirrel cage fan has blades that curve toward the direction of fan rotation. They deliver low to medium volumes at low pressures. Their low rotational speed for a given air volume makes them quiet in operation. The blade shape tends to collect dust and liquid, making these fans unsuitable for acid mists and other dirty particulate exhaust streams.

A BI blade centrifugal fan has blades that are inclined away from the direction of rotation. They can deliver air against a high enough pressure drop to be used with fume scrubbers. Their high efficiency and nonoverloading characteristics make BI fans a good choice for many exhaust applications. Although they can handle a higher dust loading than forward curved fans, they are not the ideal choice for highly abrasive exhaust streams. The BI wheel fans are the most commonly used centrifugal exhaust fans for open surface tank ventilation. The exhaust fan is usually placed downstream of any scrubber or other pollution-control device being used to minimize buildup of material on the fan blades.

Radial blade centrifugal fans have blades similar to those of a paddle wheel. This blade orientation limits material buildup and the moderate rotation speed means particles move along the blades at lower velocities than in all but forward curved fans. Radial blade fans are, therefore, widely used for industrial applications where heavily dust laden streams are being exhausted. This type of fan can provide a high static pressure and can be a low maintenance item because of its heavy duty construction. Radial fans have somewhat lower efficiency than other industrial fans, which is the trade-off for its advantages.

FAN SELECTION

Fan selection for any exhaust application must be based on matching the fan flow characteristics to the desired flow and resistance of the system. The flow characteristics of a particular fan are determined empirically by the fan manufacturer. The desired flow and resistance are calculated in the exhaust system design, as discussed previously.

The purchase price for a particular size and type of exhaust fan can vary considerably depending on the materials of construction. The greatest cost differential is between fans of FRP construction and those of epoxy-coated steel, with the FRP fan costing nearly twice as much as the epoxy steel fan. Air Movement and Control Association (AMCA) classes types A, B and C are for spark-proof fans and are required for exhausting flammable vapors such as nonhalogenated solvents.

In the metal-finishing industry, where fumes and mists of highly corrosive natures are handled by the exhaust system, PVC or FRP are the two best materials available for the parts of the fan that come into contact with the gas stream. Often, the entire fan and housing, except of course the motor, will be made of either PVC or FRP. FRP has good corrosion resistance to many acids, ammonia, chlorine, sodium hydroxide, and other chemicals up to 180°F. Vinyl-ester-based FRP is generally used for fan wheels because of its strength and ductility. Fan housings are typically made of polyester-based FRP. As PVC does not have the strength of FRP, its use for fan wheels is generally limited to PVC-coated steel or steel-reinforced PVC. Even though PVC has excellent abrasion resistance, it should not be used for exhaust air streams containing organic solvents, and it is limited to temperatures below 150°F. PVC is significantly less expensive than FRP for use in exhaust fans.

Another choice made in selecting the proper exhaust fan is the use of a belt-driven or direct-driven motor. A belt drive allows for easily varying the fan speed with changing system resistance, within the limitations of the motor used. The fan laws govern the new operating point reached when the fan speed is changed. For a given duct system, the flow will vary directly with the fan speed, static pressure will vary directly with the square of the fan speed, and power required will vary directly with the cube of the fan speed.

When specifying an exhaust fan, the materials of construction, operating characteristics, testing procedures, and any special features, such as spark resistance, should be outlined. Reference should be made to any applicable standards. the standard for FRP fans, for example, is American Society for Testing and Materials (ASTM) D 4167 entitled "Standard Specification for Fiber-Reinforced Plastic Fans and Blowers." The exhaust fan standards of AMCA should also be consulted in this regard.Optional accessories such as cleanout doors, bottom drains, and weather covers should be considered when purchasing an exhaust fan. A bottom drain is especially important for fans handling hot exhaust streams with condensable vapors that would tend to collect in the fan casing. The mists vented from plating tanks or scrubbers collect in the exhaust fan and must be drained.

The belt tension must be checked periodically to assure that the fan is rotating at the proper speed. Belts do break occasionally and must be replaced.

Fan bearings must be adequately lubricated and aligned. The fan wheel should be checked regularly for buildup of dirt, and it should be cleaned if necessary. Any dynamic imbalance caused by excessive corrosion should be corrected to prevent damage to the bearings. Although adding flexibility to an exhaust fan, belt drives involve more maintenance.

If properly selected, an exhaust fan need not be a high-maintenance item. Corrosion is the most common cause of fan failure, therefore, much of the effort in maintaining an exhaust fan should involve inspection of the fan wheel and casing for the effects of corrosion.

MAKE-UP AIR

The air that is removed from a workplace by the exhaust ventilation system must be replaced with clean air. This can occur passively through infiltration or actively via a make-up air supply system. In modern industrial facilities, infiltration is almost never sufficient to provide the needed replacement air. When insufficient air reaches the workplace, the area becomes "air starved." This puts an added burden on the exhaust system and can reduce the quantity of air being exhausted to an unacceptably low level. Uncontrolled influx of replacement air to the plating area can cause air-distribution and temperature-regulation problems elsewhere in the plant. Compensating measures taken to maintain comfort in those areas ultimately lead to the use of more energy than would be required by a well-designed make-up air system. For these reasons, make-up air systems providing tempered air to replace the exhausted air are highly desirable.

Make-up air is usually supplied by a roof-mounted supply fan equipped with air filters and some method of heating the air. Direct-fired heating of the air with gas is the most energy-efficient method. The combustion products are usually not a concern because high air flow rates provide sufficient dilution. Steam is a commonly used heating medium. Its disadvantages include freezing problems in the winter and relatively slow response to changing air temperatures. Natural gas is the most desirable heating fuel.

The distribution of make-up air in the workplace is also important from the standpoint of worker comfort, as well as proper operation of the exhaust system. Drafts on workers should be avoided in winter, but may be desirable during the summer. This can be accomplished through the use of a louver arrangement, which allows for enough flexibility in air distribution. Crossdrafts over the tops of vented tanks should be avoided.

Rather than provide 100% outside air for make-up air, it is sometimes feasible to recirculate exhausted air into the workplace. This can reduce the energy requirements of the ventilation system, because heating or cooling of the recirculated air is usually not required. This technique is generally not advisable for the plating industry, however, because of the risk of reintroducing contaminated air into occupied areas.

According to the ACGIH, the requirements for a safe, reliable recirculation system are:

1. A primary air cleaning system designed to reduce all contaminants in the recirculated air below the TLV.

2. A secondary air cleaning system of equal or greater efficiency in series with the primary system, or a reliable monitoring device to analyze a representative sample of the recirculated air.

3. A warning alarm system with provisions for immediate bypass of the recirculated air in the event that contaminant concentrations above preset limits are detected by the monitor, or the air cleaning system requires attention.

Recirculation from wet scrubbers employed for plating and metal finishing is generally not recommended because of difficulties associated with continuous direct monitoring of air contaminants at the scrubber discharge. Commercially available "recirculation packages" generally monitor scrubber performance only indirectly by monitoring fresh water feed rate, pressure drop, and/or scrubbing solution pH. Introduction of humidity into the workspace from wet scrubbers is also a concern.

Although not generally recommended for the metal-finishing industry because of the inherent difficulties and hazards, there are certain conditions that may make a recirculation system more feasible. If a process is to be completely isolated from workers, recirculation of that isolated exhaust air directly back to the process could be considered. If exhaust contaminants are only of the nuisance type rather than being toxic, recirculation might be feasible. Partial recirculation could be utilized to gain some energy savings while minimizing the risk of contaminants being supplied to the workplace.

Heat exchangers are often considered for recovering heat from exhaust air prior to discharge. Heat exchangers of any kind are rarely used for plating exhausts because of the severely corrosive nature of acidic exhausts. The use of protective coatings on heat transfer devices has met with limited success. Exhaust air is usually at room temperature, which limits the heat available for recovery. Maintenance and equipment-replacement costs associated with corrosion generally convert marginal economic feasibility into infeasibility.

Local exhaust ventilation and make-up air systems require substantial space allocations, both overhead and on the roof. Careful consideration should be given to these requirements when designing the ventilation systems. Interferences between supply and exhaust ductwork can easily be avoided through proper planning, layout, and design. Locating the make-up air unit as far from the scrubber/exhaust fan as practical, for example, will minimize the possibility of large ducts (headers) crossing each other. This, in turn, may reduce the overall building height requirement and result in substantial cost savings. The distance between any make-up air intakes and exhaust gas discharges, and their orientations relative to the prevailing wind direction, should be such that there is no significant introduction of contaminants into the make-up air supply and subsequently into the building.

AIR POLLUTION CONTROL

Air discharge limitations have become stricter in the last few years due to increasing concerns about the effects of air pollution. Regulations at the federal and state levels have reduced allowable emission rates of many compounds and will continue to be revised to regulate more sources of air pollution as deemed appropriate. Sources subject to emission limitations most often need to control a large part of their emissions with an air pollution control device. Sources not specifically subject to an emission limitation may also need to control emissions because of localized effects of emissions. Such effects can be equipment damage from long-term exposure of untreated discharges, impacts of emissions on especially sensitive areas, and excessive impact due to location of the source.

The technologies and air pollution control methods that need to be considered when evaluating emission control can be one of three strategies: add-on controls, reformulation, or process modification. In determining the required level of control, all three of these must be considered as possible reduction techniques. Often, the latter two methods are overlooked, yet it is in the best interest of a source to consider all reduction techniques. Further, regulatory agencies will often require such a comprehensive evaluation.

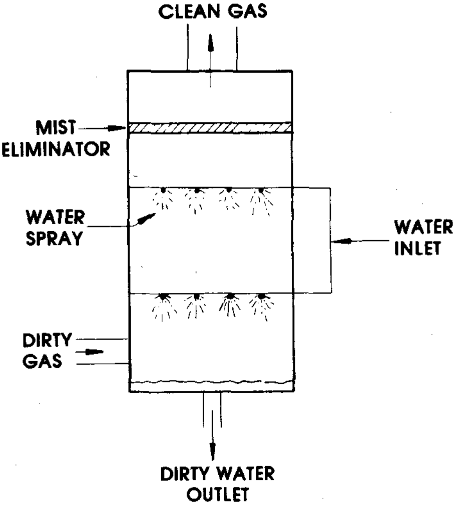


Figure 4. Spray chamber scrubber.

The traditional method of pollution control is the add-on control device. Some types of add-on devices for control are incinerators, condensers, carbon adsorbers, scrubbers, and fabric filters, to name a few. These units are placed on the exhaust stream from the process and have the advantage of requiring minimal changes in the process itself. Such devices, however, are often very expensive to purchase, operate, and maintain and can substitute one pollution problem (air) for another (contaminated water discharge or hazardous waste generation). However, these devices, often referred to as end-of-pipe control, are necessary in many cases.

The type of pollution problem will dictate the type of add-on control device used. In the metal-finishing industry, pollutants of concern are volatile organic compounds (VOCs) and acid/alkali mists/particulates and vapors. The most common sources of VOCs in metal finishing are solvents contained in paints, coatings, and organic solvent cleaning operations. Acid/alkali mists are entrained in the local exhaust ventilation of many finishing operations. Potential also exists for other emissions, such as cyanide compounds, and to a small degree, metals.

The available control devices for each of these problems can be divided into two categories, VOC control and particulate control.

VOCs, the major focus of much air pollution regulation, require sophisticated control techniques. Incinerators or afterburners oxidize organics to carbon dioxide and water and are found on some coating operations. Complications arise from inefficient combustion or contaminants other than simple hydrocarbons in the exhaust stream. Depending on the VOC being controlled, the incinerator itself may need a control device to remove undesirable products of combustion (such as hydrogen chloride in the case of a chlorinated compound being incinerated). The advantage of incineration is that, under proper circumstances, there is no secondary disposal concern. In contrast, other VOC control devices do not destroy pollutants, but collect them for reuse or disposal. Condensers work by cooling the air stream to a point where the organics condense to a liquid and are collected. Carbon adsorbers pass the contaminated exhaust stream through a bed of activated carbon, which retains the

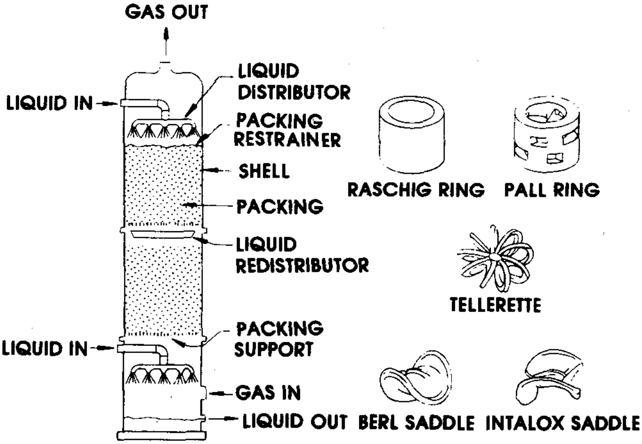


Figure 5. Packed bed scrubber with common packing types.

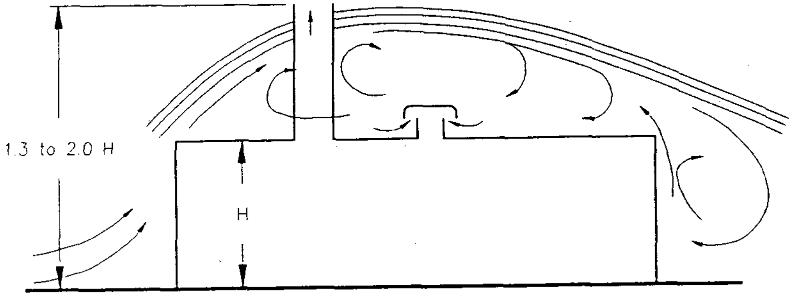
volatiles. The carbon is then stripped of the adsorbed VOC by heat and the organics are collected.

In the metal-finishing industry, wet collectors (also called scrubbers) are the most suitable pollution-control devices for removing acid/alkali pollutants. In the simplest scrubber, a spray chamber scrubber (Fig. 4), water droplets are continuously sprayed into the gas stream, where water-soluble contaminants are absorbed by the droplets. The fan pulls the air through the spray and a mist eliminator, and then releases it to atmosphere, free of the water-soluble contaminants. The mist eliminator traps water droplets and mists carried by the momentum of the air from being released through the stack.

Packed bed scrubbers (Fig. 5) are the most efficient of the commonly used wet collectors. They are similar to spray chamber scrubbers, but are filled with a packing material that increases gas–liquid contact. The gas stream enters the chamber from the bottom and the absorbing liquid (typically water) is sprayed onto the packing material from the top. The water trickles downward through the packing, while the gas stream passes upward through the packing and water. The large surface area for gas–liquid contact makes packed bed scrubbers highly efficient for both water-soluble gas and mist removal.

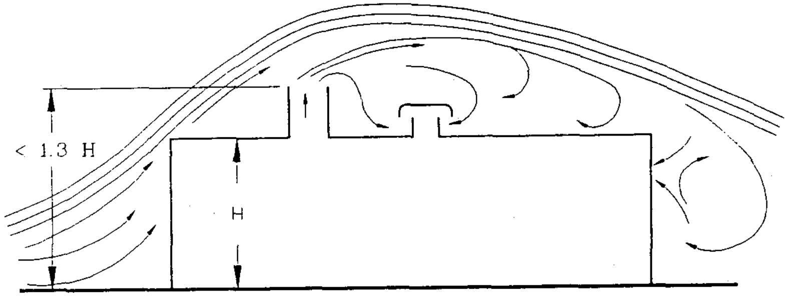
Although most scrubbers can readily achieve mist removal efficiencies of 90–99%, it is important to choose the proper scrubber to maximize its gaseous removal efficiency. The physical and chemical characteristics of the gas stream are important when deciding on the type of scrubber needed. Characteristics such as volume of collected air, contaminant solubility in water, stability of the contaminants in the gas stream, and droplets may indicate a preference for a particular type of scrubber.

Once a scrubber has been chosen, certain features can be added or changed that will increase the scubber's efficiency. Installation of high-pressure nozzles achieves smaller droplet size and higher droplet velocity, which increases gas–liquid contact and subsequently increases the removal efficiency of a spray chamber scrubber. However, high-pressure nozzles plug easily and are more expensive. Introducing the air flow to the spray chamber scrubbers tangentially will impose a spiral motion to the gas stream. The spiral motion will force a large percentage of the gas flow to the walls of the chamber where the spray is directed. The packing material in packed bed scrubbers can be changed to increase surface area and,



PREFERRED

High discharge stack relative to building height, air inlet on roof.



AVOID

Figure 6. A high discharge stack relative to building height (top) is preferred. A low discharge stack relative to building height and air inlets (bottom) should be avoided. These figures apply only to the simple case of a low building without surrounding obstructions on reasonably level terrain. Note that low pressure on the lee of a building may cause the return of contaminants into the building through openings.

subsequently, gas–liquid contact. A water redistributor midway through the packing redisperses the water flow evenly to ensure uniform water flow throughout the scrubber. In any acid scrubbing system, maintaining an alkaline pH will also increase removal efficiency.

Spray chamber scrubbers generally use a system where the absorbing liquid is collected at the bottom of the chamber and then is completely removed from the system. Packed bed scrubbers recirculate relatively large amounts of the collected absorbing liquid back into the spray stream. Contaminated absorbing liquid is removed from the recirculation loop at approximately 0.1–0.3 gpm/1,000 cfm of exhaust air. The absorbing liquid recirculation is approximately 5–15 gpm/1,000 cfm. Recirculation offers cost savings by reducing the quantity of fresh absorbing liquid required to operate the scrubber efficiently.

Corrosion-resistant plastics are most commonly used for construction of scrubbers and exhaust-handling ducts in the plating and metal-finishing industry. Plastic scrubber housings are typically fabricated of rigid PVC or of FRP. Internals are usually a combination of PVC, FRP, and polypropylene, and sometimes stainless steel materials.

If water-recirculating scrubbers are located outdoors, remote indoor sumps constructed of corrosion-resistant materials are required for freeze protection.

Wet scrubbers are not suitable devices for VOC control because most VOCs are insoluble in the water-based absorbing liquid. Exhausts from processes using VOCs should be separate from all aqueous process exhausts. State air-quality authorities may require control of significant quantities of VOCs by activated carbon adsorption, thermal oxidation, or process modifications.

Initial cost should be one of a number of factors to consider when purchasing air pollution control equipment. The physical and chemical properties of the pollution problem, as well as the maintenance, service, and operational costs, must be matched with the available control technology to ensure the most efficient purchase.

The most environmentally sound and often cost-effective method of pollution control is process modification. Sometimes, with moderate effort, less polluting ways of achieving the same result can be found. New formulations of many coatings and other VOC-containing compounds exist that have reduced or eliminated organic solvents. Many water-based paints are readily available with performance similar to conventional paints. There is constant development of new formulations that contain less VOCs and are as easy to use as previous products. In actual plating operations, sometimes less polluting alternatives can be found. The replacement of cyanide plating operations with noncyanide operations eliminates cyanide emissions.

Process changes can be a difficult course to follow in emission reductions because of the myriad choices sometimes available, as well as the scarcity of guidance offered by regulatory officials.

EXHAUST DISCHARGE

After the exhaust fan and/or control device, the exhaust gas is vented to the atmosphere through a stack. Even if the exhaust gas has been cleaned by a control device, low concentrations of hazardous chemicals may be present. Ambient air currents mix and diffuse the gas as it is emitted from the stack. Air currents are affected by nearby buildings and equipment, and the wake effect created may cause pollutants from the stack to reach the ground at objectionally high concentrations (see Fig. 6). Stack design is critical to ensure adequate ambient dilution of the exhaust. The stack should be designed so that the exhaust momentum carries the gas straight up and above buildings or equipment that may disrupt the air currents. "Rain hats," or any other structure on the stack that disrupts the upward momentum are not recommended. Stack height above ground should be at least one and one-half to two times that of the tallest adjacent structures, where practical.

WASTEWATER TREATMENT

by Thomas J. Weber

Wastewater Management Inc., Cleveland

Today, some 15,000 companies in the United States perform electroplating and metal finishing operations. These firms discharge their spent process wastewaters either directly to rivers and streams, or indirectly to Publicly Owned Treatment Works (POTWs). Metal finishing, by far, comprises more individual wastewater discharges than any other industrial category. Typically, pollutants contained in metal finishing process waters are potentially hazardous, therefore, to comply with Clean Water Act requirements, the wastewaters must be treated, or contamination otherwise removed, before being discharged to waterways or POTWs. Regulations, in general, require oxidation of cyanides, reduction of hexavalent chromium, removal of heavy metals, and pH control.

Understandably, for companies discharging wastewater directly to waterways (direct discharges), regulations promulgated through the years require attainment of the more stringent concentration-based limitations for toxic wastewater constituents necessary for protection of aquatic life. These stream standards were developed from Federal Water Quality Criteria and limit in-stream pollutant concentrations to levels that will not adversely affect drinking water quality and aquatic life. Since the mid 70s, state agencies have continued to drive direct discharge limitations downward to levels well below water-quality-based stream standards, using antidegration, antibacksliding, and existing effluent quality (EEQ) policies, and the number of direct dischargers has dropped precipitously. Implementation of biological-based criteria through biomonitoring and bioassay testing will continue to force direct discharging facility closures and relocation to POTWs.

As the overwhelming majority of metal finishing companies are discharging to POTWs, wastewater treatment systems for these firms are installed for compliance with federal pretreatment standards, or local pretreatment limitations if more stringent than the federal regulations. Federal standards are technology-based, i.e., developed through historical sampling and testing of conventional wastewater treatment system discharges collected at select, best-operated facilities. The base level technology was called Best Practicable Control Technology Currently Available (BPCTCA), or simply BPT. The more stringent level was termed the Best Available Technology Economically Achievable (BATEA), and is usually referred to as BAT. The treatment technology of BAT differs mainly from the conventional physical-chemical treatment of BPT in that it includes subsequent polishing filtration, and normally addresses improved methods of plating bath recovery.

The purpose and intent of federal and local pretreatment regulations are to prevent the introduction of pollutants into POTWs that will interfere with their operations; to prevent the introduction of pollutants, which will pass through the POTW and contaminate receiving waterways; to prevent pollutant concentrations that are incompatible with biological processes or otherwise inhibit the process; and to reduce the pollutant concentrations of POTW sludges.

Since the pretreatment regulations became effective in 1984, the metal finishing industry has taken major strides in pollution control through wastewater treatment system installation and operation, admirably fulfilling the regulatory intent. Substantial historical reductions for all metals have been demonstrated at many POTWs nationwide.

STATUS OF WASTEWATER REGULATIONS

The federal regulations listed in Tables I and II have now been in existence in excess of 10 years since the 1984 compliance dates. For those metal finishing companies still fortunate to be limited by these regulations, each limit and the applicability of the regulations are of

Table I. Electroplating Job Shop Effluent Guidelines—Pretreatment Standards for Existing Sources Greater than 10,000 gal/day

Pollutant	*Maximum for any 1 day*	*Average of daily values for 4 consecutive monitoring days shall not exceed*
Cadmium	1.2	0.7
Chrome	7.0	4.0
Copper	4.5	2.7
Lead	0.6	0.4
Nickel	4.1	2.6
Zinc	4.2	2.6
Cyanide, total	1.9	1.0
Total metals[a]	10.5	6.8
Total toxic organics	2.13	—

All values in mg/L; total metals is the sum of chromium, copper, nickel, and zinc.

intimate familiarity and compliance is being achieved on a day-to-day basis. Increasingly, POTWs are imposing, or are being forced to impose, local pretreatment limitations that are much more stringent than the federal regulations. Often, these local limits are 10–25% of the Table I and II concentrations.

Properly selecting wastewater treatment technology, modifying production operations and processes, and improving waste minimization and resource recovery techniques have become prerequisite to achieving compliance. Implementation of the basic BPT and BAT technologies is often inadequate to meet frequently unreasonable, and usually unnecessary, local limits set far below the technology-based standards. Increasingly, local limitations are being based on mathematical models using faulty software programs and arbitrary POTW effluent standards, rather than good science and environmental ncessity.

Although federal regulations have remained unchanged since their 1984 effective date, the U.S. EPA proposes to get back into the act of tightening pretreatment standards for metal finishers. In late 1994, the U.S. EPA proposed drafting Metal Products and Machinery (MP&M) Effluent Guidelines, which would impose specific concentration limitations on many metal fabricating and machine shops presently not covered under any federal industrial pretreatment category. U.S. EPA estimates the regulation would bring another 20,000 companies nationwide under the pretreatment requirement umbrella. The proposal, however,

Table II. Metal Finishing Pretreatment Standards for Dischargers to POTWs

	Existing Source		*New Source*	
Parameter	*1-day maximum*	*30-day average*	*1-day maximum*	*30-day average*
Cadmium	0.69	0.26	0.11	0.07
Chrome	2.77	1.71	2.77	1.71
Copper	3.38	2.07	3.38	2.07
Lead	0.69	0.43	0.69	0.43
Nickel	3.98	2.38	3.98	2.38
Silver	0.43	0.24	0.43	0.24
Zinc	2.61	1.48	2.61	1.48
Cyanide, total	1.20	0.65	1.20	0.65
Cyanide, amenable	0.86	0.32	0.86	0.32
Total toxic organics	2.13	—	2.13	—

POTW, publicly owned treatment works.
All values in mg/L.

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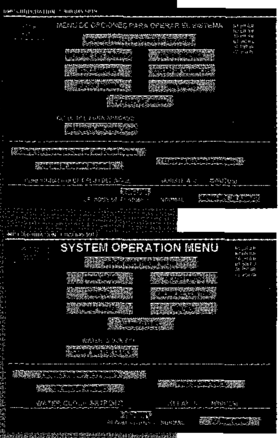

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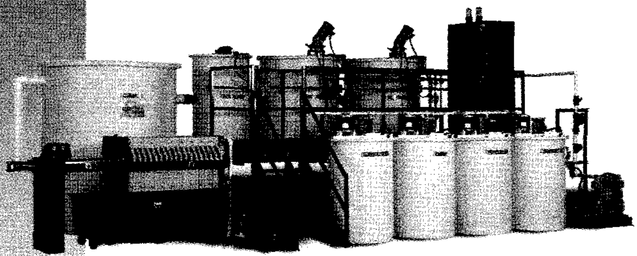

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includes the prospect of shifting all metal finishers and electroplaters to the MP&M Guidelines, thus eliminating the current regulations. The MP&M limits are expected to be developed from reassessing technology-based pollutant concentrations. This could effectively reduce federal pretreatment limitations by 50–90%, depending on the pollutant, as current effluent quality among metal finishers is much lower, for many reasons, than in the 1970s when the original BPTs/BATs were established.

Although metal finishing and POTW effluent quality have continued to improve annually, the incidence of enforcement actions and amounts of the resultant penalties have increased. Many municipalities have adopted "automatic" penalties for any discharge violation, and have modified pretreatment ordinances to make it easier to collect penalties.

The U.S. EPA was required to draft the MP&M Guidelines in March, 1995. As of the date of this writing, the regulation has not been published. If the regulation is drafted per the original proposal, future regulatory enforcement will be more likely to increase. Improved treatment system operation and performance will become an even greater economic necessity of the metal finisher.

Furthermore, the treatment focus will further shift from conventional physical-chemical treatment to the more advanced, more expensive treatment methods of microfiltration and ion exchange polishing, and closed-loop, zero-discharge methods of reverse osmosis and evaporation.

SYSTEM SELECTION CRITERIA

Four major factors contribute to the size, complexity, and cost of conventional wastewater treatment systems.

Pollutant Type

The complexity of the treatment system needed to effectively remove pollutants from a wastewater is determined by the type and nature of the pollutants encountered. A basic system will only require simple neutralization and chemical precipitation prior to solids separation for certain, although few, metal finishers. The process use of complexing or chelating agents in production baths would increase system complexity, often requiring two-stage treatment or neutralization and the need to apply chemical coagulants or specialty metal precipitants to reduce metal solubility.

Other pretreatment processes, including hexavalent chromium reduction and cyanide oxidation, are only required when the plating operation utilizes these common chemicals. Oil separation on a segregative basis may be necessary in facilities where oil and grease concentrations in the combined raw wastewater exceed 200 mg/L.

Increasingly, today's metal finishers are modifying processes and getting rid of certain finishes to eliminate problem pollutants and the resultant system complexity, or simply to reduce discharge violations. Over the years, there has been a major industry shift to noncyanide bath finishes. Curbing or modifying the use of complexing chemicals and conversion to trivalent chromium finishes has further reduced system complexity through changes in pollutant type.

Pollutant Loading

Treatment chemical costs and solids handling equipment sizes/costs increase proportionally to pollutant loading to the wastewater treatment system. Clarification, sludge storage, filter presses, and sludge dryers are sized in accordance to projected loads and solids generation. Increased size requirements result in higher capital equipment costs and higher disposal costs for waste residuals.

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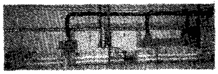

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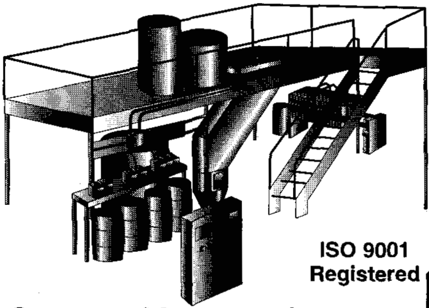

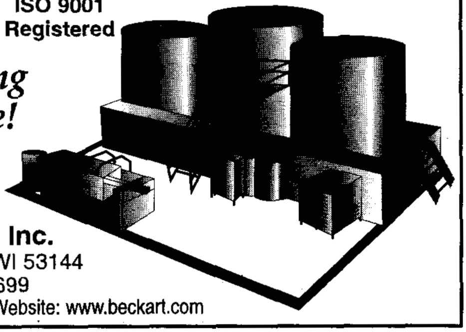

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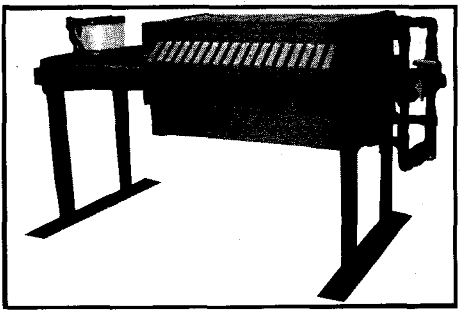

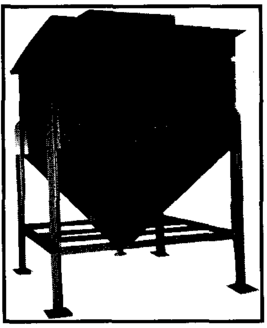

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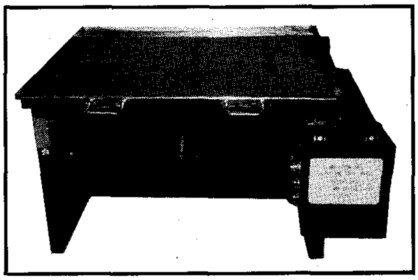

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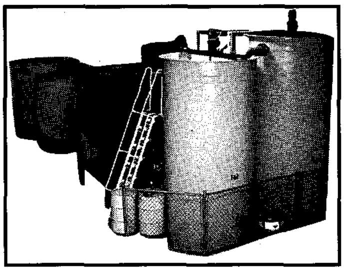

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Proper selection of plating baths with reduced metal maintenance levels and precise control of bath concentrations will reduce loadings. Other common loading minimization practices include implementing a rigorous housekeeping program to locate and repair leaks around process baths, replacing faulty insulation on plating racks to prevent excessive solution drag-out, installing drip trays where needed, etc.; using spray rinses or air knives to minimize solution drag-out from plating baths; recycling rinse water to plating baths to compensate for surface evaporation losses; using spent process solutions as wastewater treatment reagents (acid and alkaline cleaning baths are obvious examples); using minimum process bath chemical concentrations; installing recovery processes to reclaim plating chemicals from rinse waters for recycle to the plating bath; and using process bath purification to control the level of impurities and prolong the bath's service life.

Hydraulic Flow Rates

The size and capital costs for wastewater treatment are largely dependent on the instantaneous flow rate of wastewater requiring treatment. The major contributor to the volume of wastewater requiring treatment is rinse water used in the production processes coming in direct contact with the workpiece. The conversion to air-cooled rectifiers from water-cooled rectifiers, and installation of chillers and cooling towers for reuse of bath and rectifier cooling water, have largely eliminated noncontact hydraulic loadings.

Other common practices used to reduce wastewater volume include implementing rigorous housekeeping practices to locate and repair water leaks quickly; employing multiple counterflow rinse tanks to reduce rinse water use substantially; employing spray rinses to minimize rinse water use; using conductivity cells to avoid excess dilution in the rinse tanks; installing flow regulators to minimize water use; and reusing contaminated rinse water and treated wastewater where feasible.

Negative results impacting treatment system operation, however, have resulted from zealous water-reduction programs. Rinse water reductions invariably result in increased contaminant concentrations undergoing treatment, and occasionally to problem levels. Increases in alkaline cleaner and chelating chemical concentrations, in particular, commonly impede conventional treatment, resulting in poor coagulation and floccuation.

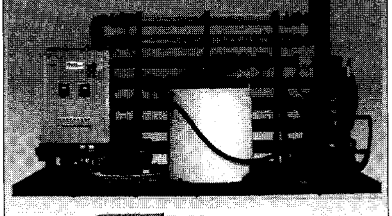
Environmental Regulations

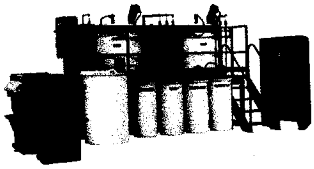
The stringency of the concentration-based discharge limitations affecting a metal finisher is often the leading criterion in selecting treatment processes and systems. Generally, conventional chemical precipitation systems, perhaps with polishing filtration, are suitable to attain compliance with federal regulations or reasonable local standards.

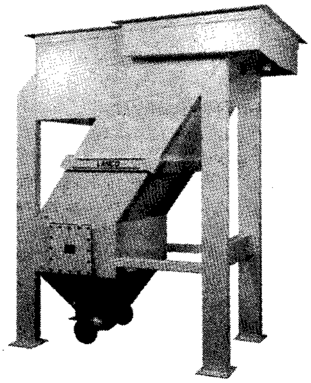
For those firms residing in communities that have adopted local standards with metals limitations ranging from 0.1 to 1.0 mg/L, cost and complexity of the system can be substantial. Multiple conventional treatment trains in series operations are relatively simple, but effective. Advanced microfiltration, cation exchange polishing, reverse osmosis, and complete evaporation may be necessary to meet stringent standards or totally eliminate the discharge.

CONVENTIONAL METHOD OF WASTEWATER TREATMENT

To this day, the majority of metal finishers are meeting, or attempting to meet, effluent limitations by treating wastewater by conventional physical-chemical treatment. The process basically involves the use of chemicals to react with soluble pollutants to produce insoluble byproduct precipitants, which are removed by physical separation via clarification and/or filtration.







Conventional treatment systems often include hexavalent chromium reduction, cyanide oxidation, and chemical precipitation in a neutralization tank. Typically, these steps are followed by clarification. As clarification is not a 100% solids separation device, additional polishing is often required using one of many filtration devices. Increasingly, it is becoming common to eliminate the clarification stage totally, and its polymer flocculation step, in favor of direct microfiltration. The sludge from either separation stage is stored/thickened in a sludge tank, then dewatered via a filter press.

Chromium Reduction

Chromium in metal finishing is normally used in the hexavalent ion form (Cr^{6+}) in plating or chromating. As it soluble at all pH values, the chemical reduction step to its trivalent (Cr^{3+}) form is necessary to ensure removal by precipitation. Commonly, trivalent chromium replacement processes are being employed for safety considerations and the elimination of the reduction wastewater step. Exercise care in selecting trichromium replacements that may contain ammonia and other chemicals, which can cause complexing of other metals in waste treatment.

The reduction of hexavalent chromium is achieved by reaction with sulfur dioxide gas (SO_2), or more commonly sodium metabisulfite (MBS). The speed of the reaction is pH dependent. At pH 2.5–3, the reaction is virtually instantaneous. Above pH 4, the reaction slows to a point where it becomes impractical for use in continuous flow systems.

The use of pH and oxidation-reduction potential (ORP) controllers is common. Without automatic pH controllers, care must be exercised to ensure complete reaction, particularly in batch reactors where the pH is manually adjusted to pH 2.5 prior to MBS addition. MBS addition raises the pH of the solution, often to ranges where reduction times are lengthy. As batch processes are usually controlled visually by color change, a significant MBS overfeed often results.

Although MBS and SO_2 are the most common chemical reducers used in hexavalent chromium reduction, any strong reducing agent will suffice. Ferrous iron in many forms, including ferrous sulfate, ferrous chloride, ferrous hydrosulfide, or electrochemical ferrous production from iron electrodes, is used.

The primary benefit of ferrous reduction is that Fe^{2+} will reduce hexavalent chromium at near neutral pH values. For low concentration applications (moderate chromating use processes), ferrous addition can eliminate the complete chromium reduction stage. The ferric ion formed in the process becomes an excellent coagulant in the precipitation stage.

The only drawback to ferrous reduction is the additional sludge generated by its use, as three parts Fe^{2+} is required to reduce one part Cr^{6+}.

Chromium Reduction Process Precautions

1. SO_2 and MBS form noxious acidic vapors. Avoid excess formation and inhalation of the vapors.
2. pH control is very important. Allowing pH to drift below 2 increases SO_2 gassing vapors. Allowing pH drift upward to 4 increases reaction times to impractical levels.
3. Underfeed of SO_2/MBS causes chrome carryover. Overfeed of MBS/SO_2 causes increased metal solubilities in neutralization, and reverses the particle charge and, consequently, results in poor flocculation.

Cyanide Oxidation

Treatment of cyanide (CN) in metal finishing wastewaters is most commonly performed by oxidation in an alkaline chlorination process using sodium hypochlorite (NaOCl) or chlorine gas (Cl_2). Because of the toxic danger of Cl_2 gas, NaOCl processes are considerably more common.

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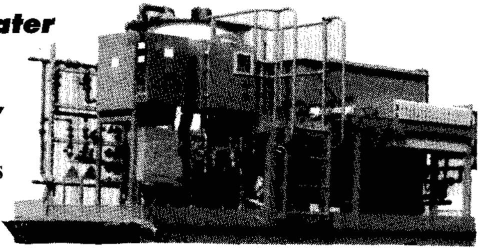

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The alkaline chlorination process either involves only first-stage CN oxidation, whereby simple cyanides are converted to cyanates (OCN), or the addition of a second-stage reactor to convert cyanates to carbon dioxide (CO_2) and nitrogen (N_2).

First-stage CN oxidation is carried out at a pH of 10.5 or higher. The reaction slows greatly at pH values below 10 and virtually ceases at pH values below 9. The process only oxidizes simple cyanides, such as NaCN, KCN, $Zn(CN)_2$, CdCN, CuCN, etc. Complexed cyanides, commonly found in metal finishing wastewater as iron complexes, are not destroyed in alkaline chlorination processes. In fact, complexed cyanides are not destroyed efficiently by any common cyanide oxidation process, including ozone. The use of high-pressure/high-temperature thermal processes will, however, destroy complexes. Also, lengthy exposure to sunlight will convert complexed cyanides to simple cyanides, to a small extent.

As federal and local regulations are generally written for total cyanide monitoring and limiting, complex cyanides are often the species causing violations.

Complexed cyanides are most commonly formed by poor housekeeping, control, and rinsing. Drag-out or drippage of CN from baths or bath rinses into acids and chromates is very common. Steel electrode use in plating baths causes a significant amount of complexed cyanide input to the bath from constant decomposition. Clean steel parts allowed to fall and accumulate in CN baths are another major source of complexed CN formation.

Although complexed cyanide formation cannot be totally eliminated, reduced formation through housekeeping and improved rinsing can reduce the concentration to nonproblem levels.

Complexed cyanides are generated in both soluble and insoluble forms. The insoluble form is removed via mass settling in the clarifier. Conversion of soluble complexes to insoluble complexes can be achieved to some extent by the addition of MBS to the neutralization tank. The efficiency is improved in the presence of copper ion. Permanganate addition also has been reported to accomplish improved precipitation of complexed cyanides.

The second-stage CN oxidation process is carried out at a pH of 8.0–8.5. An amount of Cl_2 comparable to that required in first-stage oxidation (3.5 lb Cl_2:1 lb CN) is necessary to complete the conversion of OCN to CO_2 and N_2.

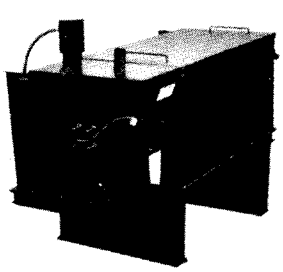
Most sewer use ordinances do not require cyanate oxidation or limit cyanate in the discharge. Consequently, many treatment systems only employ first-stage processes. A common problem associated with first-stage-only systems is the propensity to gassing in the neutralization tank, with resultant clarifier floating problems. This is caused by an uncontrollable cyanate breakdown, particularly when excess residual Cl_2 is present in the first-stage dischare.

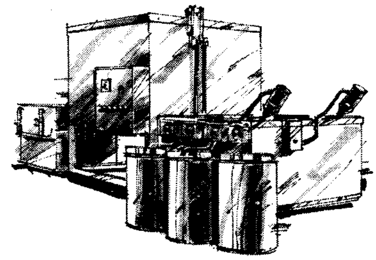
Although reaction times for most simple cyanides and cyanates are 10–15 minutes, it is advisable to size reaction tanks at 1 hour and longer if affordable/practical. Certain simple cyanides, including cadmium and copper, only start breaking down after the sodium, potassium, and zinc cyanides are destroyed, thus requiring longer contact periods. Furthermore, the longer the reaction, the more efficient the gas venting becomes, reducing the incidence of clarifier floating.

Because precise control of pH and Cl_2 is important, pH and ORP controllers are recommended in all continuous control reaction tanks.

Summary of Cyanide Process Precautions

1. First-stage oxidation must be controlled at pH 10.5 or higher. (The higher the pH, the faster the reaction.)
2. Control the formation of complexed cyanides, as treatment processes do not destroy them. Add MBS to the neutralization tank if soluble complexes cause effluent violations.
3. Allow 1 hour or more reaction time to ensure completion of the reactions, and for problem gas venting.
4. Underfeed of chemical allows CN pass through; overfeeds cause increased gassing and reoxidation of trichrome.





Coagulation/Neutralization Process Considerations

Effluents from hexavalent chromium reduction and cyanide oxidation stages combine with other alkaline and acid wastewater streams in a neutralization tank. The express purpose of the neutralization tank is to create a suitable environment and retention time for soluble pollutants to react and form insoluble precipitates for eventual physical separation. The principal precipitation process employed in conventional wastewater treatment systems is that of hydroxide precipitation. Heavy metals, the prime targets of neutralization-precipitation, have varying solubilities depending on pH. In common mixed-metal wastewater streams, control of the neutralization tank at pH 9.2–9.5 is generally suitable to lower metal solubilities, as hydroxides, to concentration ranges where compliance is achievable.

In many cases, it is necessary to add chemical coagulants to the wastewater in order to achieve minimum solubilities and superior flocculation/solids separation in the clarifier. A proper coagulant will effectively tie up anionic surfactants, wetters, and species such as phosphates, which interfere with polymer flocculation; and also add bulk density for improved solids separation.

Where coagulants are required for good process performance, it is recommended that two-stage neutralization reaction tanks be employed, as coagulants perform better when reacted with the wastewater at pH values in the 5.5–6.5 range.

Common chemical coagulants include calcium chloride, ferrous salts, ferric salts, and alum.

For improved coagulation, certain specialty coagulants are available from chemical suppliers. These chemicals usually contain one of the above base salts, which are sometimes blended with polymers, generally of a cationic nature. Although these specialty products are expensive, with costs ranging from $400 to $1,000 per drum, their use is often necessary to achieve compliance.

Neutralization is generally achieved using caustic soda (NaOH) and sometimes potassium hydroxide (KOH). Hydrated lime and magnesium hydroxide also have wide utilization. Although these neutralization chemicals present certain handling and feeding problems associated with their solids content, lower metals solubilities are achieved at maintenance of lower neutralization tank pH (8.0–8.5).

The introduction of strong chemical complexers used in production processes commonly impedes the pollutant precipitation process. Common complexers/chelators include ethylene diamine tetra acetic acid (EDTA), nitrilotriacetic acid (NTA), quadrol, glucconates, glutamates, ammonia, and various amies.

Complexing agents are commonly used in electroless baths, electroplating bath brighteners, alkaline cleaners, parts strippers, and numerous other applications. Eliminating their use, where practicable, is the simplest means of mitigating their adverse wastewater treatment effects. Where critical to the process, special means and practices must be employed, which vary with the type and strength of the complexer, as well as the metal(s) being complexed.

Often off-line pretreatment is necessary, as in the case of high volume electroless bath use. In other cases, the use of specialty chemical precipitants, metered into the complexed waste stream or into the neutralization tank, is suitable and effective. Specialty chemical precipitants include dithiocarbamates, dithiocarbonates, starch and cellulose xanthates, poly quaternary amines, and ozone destruction/hydrosulfite reduction.

As complexing chemicals are primary reasons for noncompliance in conventional systems, much care and time are necessary to solve the problems created by them. Often significant trial testing in bench scale treatability tests and close work with chemical suppliers are necessary to resolve complexing problems.

In some cases involving simple complexed wastewaters, conversion from hydroxide precipitation to sulfide or carbonate precipitation in the neutralization process will achieve necessary reductions in metal solubility. Most metallic sulfides and metallic carbonates have lower solubilities than their hydroxide counterparts.

Reaction times required for effective coagulation-neutralization-precipitation vary among wastewater types and complexity. We recommend minimum retention times of 30

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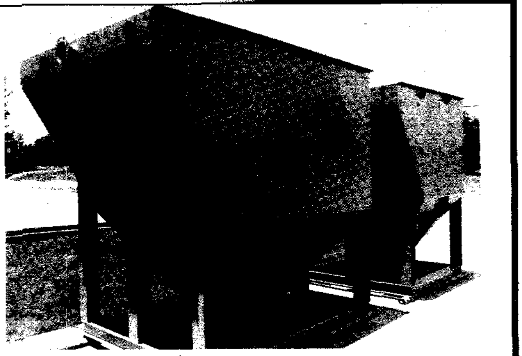

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minutes, 15 minutes in first-stage reactors. As metal hydroxides tend to reduce in volume the longer they are mixed, the longest practical reaction times are most desirable.

Common problems associated with neutralization/reaction tanks, which impede clarifier separation of solids, include soluble complexes caused by chelating agents; charge reversal caused by anionic surfactants, phosphates, and MBS overfeed; solids buoyancy or flotation problems caused by excess oil and grease or gas formation including chemical gassing caused by peroxides, acetates, and carbonates or physical-induced gassing caused by suction leaks on transfer pumps, or significant mixer vortex action; overfeed of dump solutions, particularly alkaline cleaners; and high total dissolved solids (TDS), 7,000 ppm and higher, from overly zealous water conservation practices, or high percentage reuse of treated water.

FLOCCULATION/CLARIFICATION PROCESSES

The precipitates formed by the proper operation of the coagulation-neutralization stage are commonly removed in conventional wastewater treatment systems by clarification or sedimentation. This process involves solids removal by the efficient settling of solids. Buoyancy caused by oils or floating caused by the entrainment of gas bubbles will prevent efficient settling. Generally, floating problems are controllable in the typical metal finishing wastewater installation. For certain firms, which employ electrolytic/electrochemical pretreatment or ozone generation/air diffusing treatment techniques, dissolved air flotation (DAF) is the preferred unit for solids separation.

Solids separation is improved in clarifiers, or DAF units, by polymer (polyelectrolyte) flocculation. As the average charge of metal hydroxides is positive, a negatively charged (anionic) polymer is used in the flocculation process. It is imperative that the wastewater charge remain positive at all times. Coagulants and/or cationic polymers may be necessary in certain wastewater types where charge reversal is common, as in phosphating operations. Nominal flocculation time of 1 minute is recommended for floc tank size. Variable speed mixers are recommended to allow some measure of control of floc size.

The size of the clarifier generally varies with the type and style. Basic, open/empty sedimentation tanks commonly used in low-flow installations should be sized for a maximum surface loading rate of 500 gal/day/ft^2 of tank surface.

Most commonly employed clarifiers are of the lamella type or inclined plate variety. These units are sized based on volumetric flow rate per square foot of plate pack area projected on the plate incline, or cosine of the degree of plate angle; typically 60°. Recommended loading rates are 0.2–0.4 gal/min/ft^2 of projected plate area, and a total suspended solids (TSS) concentration of 500 ppm or less.

Units are manufactured in basic hydraulic flow sizes, i.e., 30 gal/min or 75 gal/min, etc. In those cases of high TSS loads (500 ppm or higher), it is not advisable to size a unit based solely on flow. In these high solids load applications, clarifier selection should be based on 1 lb TSS per hour for each 20 ft^2 of projected clarifier settling area.

Manufacturers will supply design and operational information for their specific unit. As a general rule, it is important to evacuate sludge as it accumulates to prevent its buildup into the plate pack area. This creates blockages and increases the upflow velocity in the open areas and carries TSS with the high flow. Monthly draining is advisable to minimize ratholing and solids concretion.

EFFLUENT POLISHING

At times, clean water that overflows from a clarifier will require further removal of suspended solids or polishing to meet more stringent discharge requirements. This may be for water reuse or simply as insurance in case of a system malfunction. Sand filters, devices consisting of one or more layers of various sizes and types of granular media, are typically used. Gravel, sand, anthracite, garnet, and activated carbon are common media.

The size and number of filters is, as with a clarifier, dependent on the volume of wastewater to be filtered and the surface area of the filter media. Gravity-operated sand filters usually are loaded at 0.25–0.5 gpm/ft^2, whereas pressure sand filters can operate in the 5.0–10.0 gpm/ft^2 range, depending on the suspended solids of the effluent.

Most sand filters need to be periodically cleaned or "backflushed" to remove the solids that have built up. Clean water, process water, or dilute acid solutions may be used for this back flushing. Backflush waters are generally returned to the collection or equalization tank and returned to the treatment system. Pressure sand filters require less backwash water than larger gravity types.

Operationally, care must be taken to ensure that pumps feeding or backflushing the filters are operating at design capacity to ensure proper loading and adequate cleaning of the media. Sand filter media are rarely replaced, except when a severe system upset causes solids to block the water distribution headers.

SLUDGE THICKENING AND DEWATERING

Sludge (settled solids) produced from treatment of metal finishing wastes generally contains between 1.0 and 2.0% total solids. Disposal of such a watery sludge is very expensive. Most medium and large generators of wastewater choose to thicken and dewater sludge, thus reducing the volume of waste to be disposed.

A sludge thickener, although not always necessary prior to dewatering, serves several worthwhile functions. First, it creates storage volume for the sludge in the event that the dewatering equipment is not in operation. Second, it allows for a consistent sludge blanket level in the clarifier. Sludge can be intermittently removed from the clarifier by means of a timer on the sludge pump. This reduces the possibility of solids drafting over the clarifier weir(s) because of a high sludge blanket. Finally, sludge stored in a thickener may increase in solids content to as much 3–4%.

Increased solids content does two things: it decreases cycle time required by the dewatering equipment (filter press, centrifuge, belt press) and, as a rule of thumb, regardless of the type of dewatering equipment, the thicker the feed sludge, the drier the sludge cake. The objective is to reduce the volume to be disposed of by removing as much water as possible.

The filter press is most often used in the dewatering of metal finishing sludges because generally it is made to handle smaller volumes of sludge, is simple to operate, and produces a dry, easily disposable filter cake. Sludge from the thickener, or directly from the bottom of the clarifier, is usually pumped via an air diaphragm pump to the filter press. The polypropylene filter media retains the solids while the liquid portion or filtrate flows through the media and discharges. Filtrate usually returns to the collection/equalization tank for retreatment. After a certain length of time (2–4 hours), the chambers of the press are completely full and a filter cake of 25–35% solids has formed. The hydraulic pressure that had been holding the plates together is now released and the filter cake is discharged.

Filter press operation requires little operator attention except at the beginning and end of a press cycle. Presses without an automatic plate shifter often require two people to separate the plates to discharge the cake, one on either side of the press. Cake that has had enough time to sufficiently dewater will literally fall out of the press upon opening.

The highest operational cost involved with a filter press is the replacement of the filter cloths. Cloth life is directly dependent on the number of press cycles per year. The metal hydroxide sludges produced from treatment of metal finishing wastes are generally of moderate pH and nonabrasive. Cloth life of 1–2 years is common. Replacement of cloths is labor intensive, especially the caulked, gasketed variety, but all the cloths, even in a large press (10 ft^3), can be changed in 3–4 hours. Because plates and cloths are usually of polypropylene construction, they can be routinely cleaned by immersion in an acid without damage.

SYSTEM OPERATION AND PERFORMANCE

The best system design may result in inadequate results unless operators and management devote the necessary resources. These resources include time, talent, and training. Sufficient time is required for normal operation and routine preventive maintenance. The talent of motivated operators is necessary to anticipate problems and take preventive steps to assure continuous compliance. Training is critical for operators to understand how system performance is affected by changes in production, chemicals, or regulatory limits.

The operator needs to keep a daily log listing volumes treated, chemicals consumed, sludge produced, and effluent results. Either the operator or management should review these results to evaluate trends so costs can be controlled and results improved. For instance, increases in sludge production without corresponding increases in production may indicate increased drag-out losses, failure of recovery equipment, or changes in treatment chemistry.

Regulatory authorities require timely and accurate analytical data to confirm compliance with effluent limitations. Operators need daily analytical data to control system performance and to make needed adjustments to treatment chemistry. This is often accomplished using inexpensive troubleshooting analytical tools including pH papers in lieu of a hand-held pH meter, and potassium iodide-starch papers for cyanide oxidation process control. Quick and easy tests for CN and metals used in the process are important. A number of test kit suppliers are available to choose from. It is not always necessary to have the sophistication of a spectrophotometer or atomic absorption unit for in-house troubleshooting and quality control. It is important, however, to have this service and complete analytical services available from a competent outside laboratory. All regulatory agencies will require data submission based on approved test methods and procedures with report submittals.

It is imperative to know your regulator and communicate with him/her regarding system operations, both good and bad. Most agencies require notification of system upsets and slug loads. Although the typical metal finisher is reluctant to report problems, it is always better to report problems than for the regulator to find them. Notification always can be used as mitigation at enforcement proceedings.

COMMON MISCONCEPTIONS AMONG METAL FINISHERS ABOUT WASTEWATER TREATMENT

- Regulatory agencies only set effluent standards at reasonable levels necessary for environmental and POTW protection.
- Consultants and suppliers always know how to solve your problems.
- The use of ion exchange for complete wastewater treatment is a practical approach to eliminating discharges.
- Microfiltration is a sure method of compliance because it filters out everything.
- The cyanide oxidation system is not working well because you have total cyanide discharge violations.
- When floating in the clarifier occurs, the probable cause is oil and grease.
- A polishing filter will solve all the problems.
- Metal violations are always due to clarifier or polishing filter problems.
- All laboratories generate good data.
- pH and ORP electrodes only have to be cleaned weekly.
- If poor floc formation is observed, the polymer is bad or you're not adding enough.
- In most cases, sludge dryers will save you money.
- Clarifiers and filter press cloths do not need to be periodically cleaned.
- The pH reading on the controller is always correct.

WASTE MINIMIZATION AND RECOVERY TECHNOLOGIES

by W. J. McLay

QVF Process Systems Inc., Horseheads, N.Y.

and F. P. Reinhard

CH2M Hill, Eagan, Minn.

The surface-finishing industry is a chemical-intensive industry. A special category of chemical processes, characterized primarily as electrochemical processes, are used to treat and condition, or "finish," the surfaces of a variety of manufactured goods and components to either enhance visual appeal, improve corrosion resistance, or to increase product durability or serviceability.

Some providers of finishing services, and most manufacturers with in-house finishing operations, are understandably inclined to view themselves as purveyors of finishing services for the end products that they process or as producers of the products that are manufactured, rather than as operators of chemical plant and chemical producing processes.

Surface-finishing processes certainly fall under the definition of chemical processes. As such, they are no less subject to the limitations and laws of chemistry and physics and to good process design and chemical engineering practice.

The similarity of chemical production processes and surface-finishing processes is strong. At the heart of electroplating and waste-treatment operations, one finds many of the classic chemical unit operations and process techniques common to chemical production: mass and energy transfer, fluid flow, mixing, evaporation, reaction, sorption, crystallization, concentration/dilution, solid/liquid separation, etc.

A broad variety of chemicals is used by the finishing industry; however, only a small fraction of the chemicals purchased for bath make-up and operation is ultimately incorporated in the finished goods. While chemical manufacturing processes generate more hazardous waste on a tonnage basis, surface-finishing processes lose a disproportionate quantity of purchased chemicals as byproduct hazardous waste. The value associated with this wastage, plus the added cost of treatment and disposal, constitute major pressure on operating margins and profit.

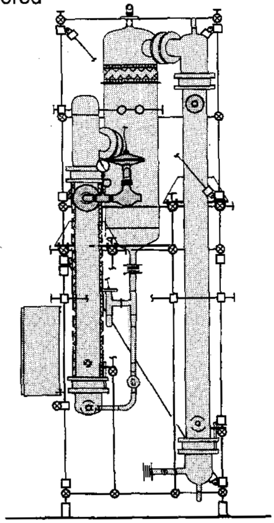
In addition, finishing operations also require equally disproportionate quantities of process water per unit of production for parts cleaning and preparation, for bath make-up and maintenance and, of course, for rinsing. In many parts of the country the availability of quality process water is becoming a major concern to the finishing industry.

The price and conditioning costs of raw water are also increasing. Many finishers are looking for practical ways to limit water usage and to recover and reuse as much process water as possible.

Some firms have achieved, or are approaching, the elusive goal of zero liquid discharge. Also, the added incentive of potentially not requiring an effluent discharge permit has strong appeal.

In addition, finishing processes cannot be operated with the same degree of control common to many chemical production processes. By definition, many chemical processes are essentially steady-state processes and lend themselves to tight statistical control. In comparison, finishing processes are more readily categorized as unsteady-state processes that are relatively chaotic from a process standpoint and, as a consequence, are more difficult to monitor and control.

This characteristic has nourished the relatively straightforward "lime-and-settle" method



of treating toxic wastes and has hindered the acceptance and application of what are now a well-documented set of chemical process techniques for reducing the high level of waste generated by surface-finishing processes.

In an ideal finishing process, there would be no bath drag-out. Chemical losses would be restricted only to those chemicals that are consumed in cleaning and preconditioning surfaces and to those portions of the plating baths, which produce the desired surface coating or condition.

In the real world, bath drag-out is, of course, unavoidable. Drag-out can be reduced to some extent by instituting such mechanisms as increasing dwell time over baths, decreasing bath surface tension, forward pumped spray rinses, air knives, etc. Despite such efforts, substantial quantities of bath can still be lost to the rinse system. The net result is that bath drag-out continues to be the primary contributor to the extraordinary quantity of chemical waste generated by the surface-finishing industry.

This article reviews a number of well-demonstrated and proven chemical recovery methods, collectively known as separation technologies, for reducing or in some cases reversing bath drag-out. When properly selected and applied, one or more of these technologies in combination can be confidently used to separate and recover dragged-out bath or specific chemical components or values of certain baths or solutions and to separate and condition rinsewaters for recycle and reuse in the plating process.

Each technology separates the constituents of a solution differently. For example, evaporation separates the solvent (water) from the rest of the bath constituents. All other techniques affect separation on either a molecular or an ionic level. The choice of technology, or combination of technologies, is determined by both bath chemistry (what the chemistry lets you do) and by the underlying operating economics.

ECONOMICS OF RECOVERY VERSUS TREATMENT

There are essentially four approaches that can be taken to evaluate point-source recovery potential in given metal-finishing operations.

Operating Savings

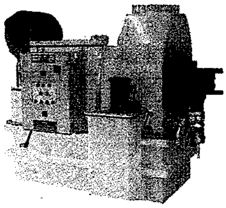
Plating facilities with existing and adequate waste treatment systems can readily assess operating savings for a candidate recovery technology. A given recovery technology is evaluated on the basis of savings on purchased process chemicals and associated waste treatment chemicals plus any resultant savings in sludge handling and disposal cost. If the payback on invested capital is attractive, the recovery system should be installed.

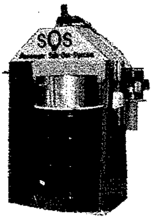
Avoidance of Waste Treatment Capital Cost

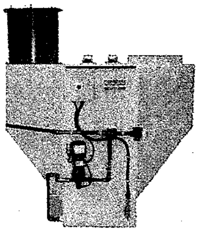
Operating cost is the primary consideration for a new plant or for existing plants with an inadequate treatment system. In this case the economic evaluation incorporates an added factor; the avoidance of additional capital investment for waste treatment capacity.

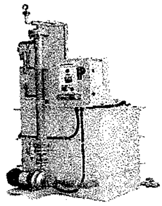
Improvement of Manufacturing Operations

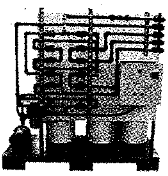
The implementation of recovery and quality maintenance methods and systems for both process water and process baths can help improve the performance of plating and surface-finishing baths and, in turn, the quality of the finish and the products that are produced. Such action will also help to reduce the amount of rejects and reworking of parts. Both aspects benefit production and quality control and will reduce operating costs and increase the value of fabricated products.











Total Avoidance of Sludge Disposal

For this scenario, justification for investment in recovery is based on the obvious desirability of eliminating generations of hazardous waste residuals. Stringent economic quantification is difficult in this case because of the uncertainty associated with determining long-term liability costs for future landfill disposal; nevertheless, there is powerful emotional appeal attached to the avoidance or minimization of long-term liability.

Evaluating Strategies

The first of these strategies is clearly the most conservative. It is easily applied and is the strategic analytical technique, which has traditionally been used by many metal finishers. The rapid escalation of sludge disposal costs makes point source recovery techniques, which were unattractive a few years ago, very enticing now.

The second strategy is legitimate but must be analyzed and applied with caution. There is a tendency to assume that recovery can be a complete substitute for treatment. Careful consideration must be given to potential downtime of recovery equipment; the generation of excess waste if the units are overloaded; the treatment of side streams such as regenerate waste or blowdown from the recovery process; accidents such as tank overflow, heat exchanger failure, spills or drips of chemicals, etc., plus unanticipated sources of regulated pollutants.

An example of the last-mentioned caution would be the presence of zinc ion contamination in the drag-out from alkaline cleaners, acid dips, and chromate dips in a zinc plating line. Too often attention is focused on recovery of the drag-out from the main plating tank, with no recognition that effluent quality may be unsatisfactory simply as a result of minor contributions from various other sources. When considering this strategy, the absolute minimum provision for unrecovered waste should be the determination of the minimum holding and treatment capacity needed to cope with the volume of unanticipated accidents or upsets.

The third strategy is the most efficient and productive way of converting waste treatment capital into waste minimization and production control efforts. Many examples today prove that the incorporation of pollution control and maintenance equipment into plating operations helps to significantly reduce batch dumps of process baths. Controlled bath maintenance limits bath impurities that cause plating quality problems and thus improve fabrication while reducing manufacturing cost. In many cases, short duration ROI objectives can be realized.

The fourth strategy is the most risky and the most difficult to support by facts. It is a rare situation where the generation of sludge can be completely eliminated, even in a theoretical sense, especially if such unanticipated occurrences as just discussed are considered.

In summary an investment in recovery technology and equipment should be supported by a hard, quantifiable economic analysis and supported by adequate operator and maintenance training. There is constant activity in the marketplace with new developments and promising breakthroughs in technology. Marketing claims can often make the situation bewildering, but it is appropriate to bear in mind that the laws of chemistry, physics, and economics will prevail. The fundamental law of ecology teaches that there is no free lunch.

Mother Nature is a tough task mistress. She has made it much easier and less costly to mix things together than to take them apart.

SOURCES OF WASTE

There are three categories of waste that must be considered when formulating a waste minimization program.

Bath Drag-Out to Rinses

This is the carryover of concentrated process baths on the workpieces, which is removed by stagnant and flowing water rinses.

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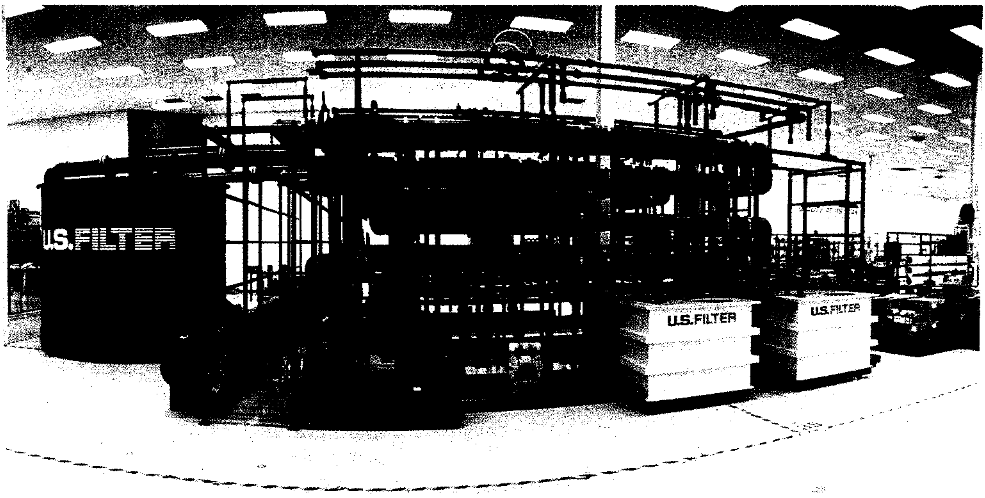

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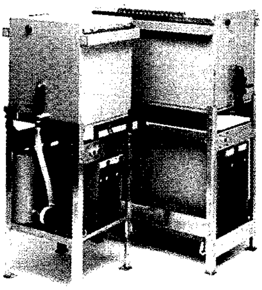

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Bath Dumps

Most of the process baths used in metal finishing are expendable and must be periodically discarded when their chemical activity is below a level acceptable for production purposes.

Floor Spills

This is a catch-all category including both accidental and purposeful incidental waste sources such as tank overflows, drips from workpieces, leaking tanks or pipes, spills of chemicals, salt encrustations, equipment and floor wash-down water, oil drips, or spills from gear boxes, etc.

Historically, most of the emphasis on recovery technologies has focused on rinsewater since it constitutes the majority of the flow leaving an operation and necessitates expensive waste treatment. Bath dumps are usually infrequent and are low in volume. Often, dumped baths can be hauled to a distant location by a waste service provider for final treatment and disposal. A subsequent section of this article will discuss the possibility of regeneration for certain of these baths to eliminate the need for periodic dumping.

Floor spills are nearly impossible to manage by the application of recovery technologies due to their unpredictable and intermittent nature and to the fact that they are so heterogeneous in composition. The primary attack on floor spills is tight operating and process control, adequate operator and safety training, programs to eliminate accidents, and, of course, good housekeeping.

The following sections will deal with the techniques applied to rinsewater. These can be divided into those that return a concentrated solution back to the originating process and those that aim to recover metals or chemicals for use elsewhere.

CONCENTRATE RECOVERY METHODS

There are a number of important factors that should be considered in regard to returning concentrate to the originating process. First, the majority of metal-finishing process baths is ultimately expendable. They have a finite life and are periodically discarded. Recycling of drag-out simply accelerates this process and will give no net gain unless some regeneration scheme is employed on the process bath itself. Thus, recovery of drag-out is most often considered only for the baths that operate in a reasonably balanced condition, primarily the process baths. A general recovery schematic for return methods is pictured in Figure 1.

In the case of those electroplating baths where return of drag-out seems practical, two factors should be examined:

1. In most cases there is a tendency for harmful impurities to accumulate over time from drag-out return. These impurities can be metals or other cations or anions dragged into the bath. Or, they can be electrolytic breakdown products normally generated during bath operation. Examples of the latter would be the formation of carbonate through anodic oxidation of cyanide or the generation of undesirable organic breakdown products formed through the electrolytic breakdown of brighteners, wetting agents, grain refiners, etc.

2. In baths that use soluble anodes, the primary metal generally has a tendency to "grow" or to accumulate in the bath. This generally occurs because the electrochemical efficiency for anodic dissolution is higher than is the efficiency of cathodic deposition and/or because the bath itself has a solubilizing effect on the anodes during periods of inactivity.

In many cases both of these effects are fortunately minimized or controlled by the routine loss of bath through drag-out, filtration, purification, and by the removal of suspended solids

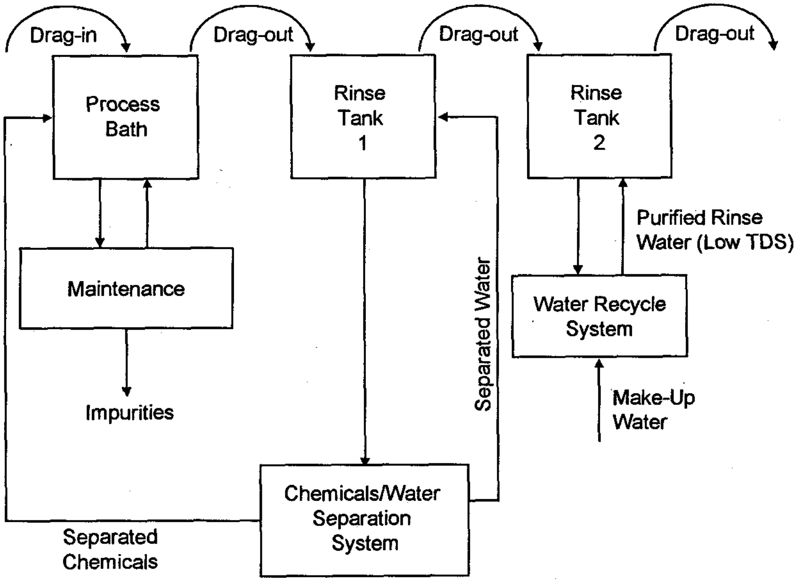

Fig. 1. General recovery schematic for return methods: evaporation, reverse osmosis, electrodialysis, ion exchange.

and sludge. In some baths, however, such as bright nickel, the accumulation of impurities can be a problem in spite of the normal losses from maintenance and purification procedures.

When a high percentage of drag-out is returned by any of the technologies that will be reviewed, it may mean that the accumulation of cationic contaminants will become evident more quickly or more frequently, requiring a purposeful bleed-off of plating bath that is obviously somewhat counterproductive. In regard to impurity accumulation, complete return of drag-out necessitates purification/maintenance operations or may increase the frequency of those already practiced. Since virtually every such operation creates loss of bath this is again an offsetting consideration to any recovery that is being gained.

A proper analysis of the optimum scheme should include all losses from the operation and the impact the recovery of drag-out will have on other sources of loss.

Evaporation

Evaporation is the oldest and most broadly applied of the separation technologies and has an extensive operating history. In the surface-finishing industry, evaporative recovery is classified as a concentrate and return technology and its track record and benefits are well demonstrated.

Evaporation is routinely used for point source separation and recovery of plating baths and their associated rinsewaters for recycle to the finishing system. Evaporation is also being used successfully to minimize liquid discharges from manufacturing plants by concentrating certain pretreated wastewaters, or brines, for haul-away and disposal while recovering additional process water for recycle to the process.

Compared to other separation methods, evaporation is more energy intensive; however, it is the only recovery technology that can treat plating rinsewaters to separate the solvent

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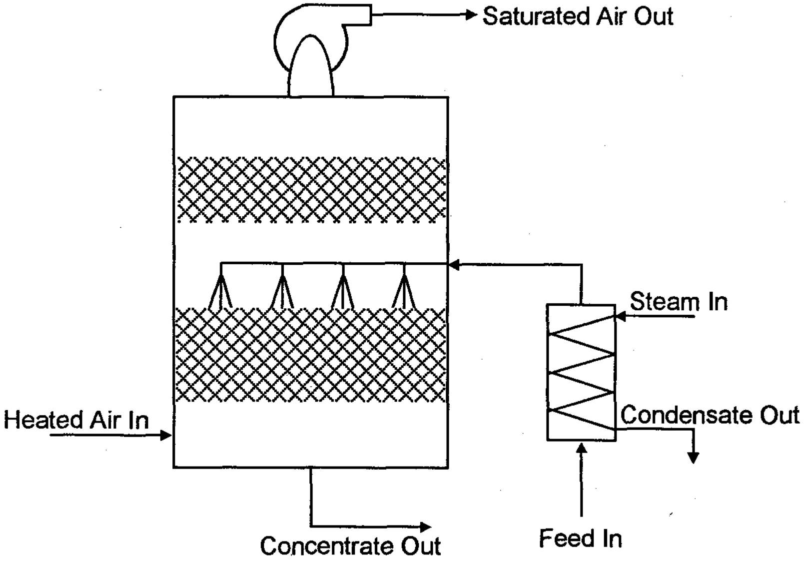


Fig. 2. Single-stage atmospheric evaporation schematic.

(water) from the dissolved chemicals and concentrate the remaining solution back to, or even beyond, bath strength. To minimize energy consumption recovery rinsewater volume can be minimized by the application of counter-current rinse hydraulics.

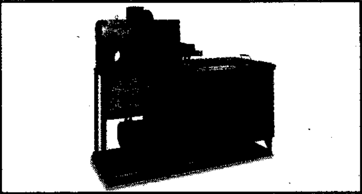
On the positive side, evaporation is a straightforward, rugged, reliable, broadly applicable, and widely practiced recovery technique. Materials of construction are available for virtually any process bath.

Evaporation separates volatile from nonvolatile constituents of a solution by means of heat-energy-driven phase change (converting liquid to vapor) resulting in a recovered concentrate. In the case of using a vapor condensation technique, atmospheric and vacuum evaporation generate a distillate that can be recovered in most cases as process water. Compared to other separation and recovery techniques evaporation can easily concentrate back to, and in some cases well beyond, bath concentration.

Heat energy is required to evaporate water from an aqueous solution. The amount of energy required is roughly 1,000 Btu/lb mass of water evaporated, regardless of whether the evaporation is conducted at atmospheric pressure or under vacuum. There is no exception to this rule! It can be called the rule of 1,000. To evaporate a pound of water, this quantity of heat energy *must* be supplied from some energy source. With the possible exception of an unlimited supply of hot, dry desert air, or of waste process heat that could be captured for use, vaporization energy is rarely "free."

Atmospheric evaporators are essentially simple scrubbing devices that use an air stream to strip water as vapor from a liquid solution. In essence, an atmospheric evaporator is an air stream humidifier. They have been widely used by industry because of their low cost and operating simplicity. Atmospheric units are generally applied singly (Fig. 2) or in multiples to dewater various plating rinse waters to recover bath concentrate.

Atmospheric evaporators operate by either pushing or pulling an air stream through a mesh bed or grid-work over which rinsewater, or in some cases, the bath itself, is circulated.



Either the air stream or the bath, or both, must be heated to provide the necessary 1,000 Btu of heat energy needed to evaporate each pound of water. Heat must be supplied from somewhere or the unit won't function.

The amount of water removed with each pass is a function of the mass, temperature, and humidity of the air stream, and of the temperature of the liquid being circulated through the unit. Heat energy is usually supplied by an external heat exchanger. If a normally hot plating bath is being circulated through the evaporator, the total heat energy required may be provided entirely by the bath itself, which, of course, will have to be reheated.

The amount of water an air stream can remove from an aqueous solution is a function of a number of factors including the relative humidity of the air at the process environment; the temperature of both the air stream and the liquid solution; the relative mass velocities of both streams through the evaporator; the degree of effective contact between both streams; and the concentration of the liquid solution being evaporated. The necessary 1,000 Btu/lb of water vaporized still must be provided.

In most atmospheric evaporator designs, the vaporized rinsewater is not captured. Instead, the humid air stream is vented to atmosphere. To avoid possible carryout and discharge of hazardous substances, the air stream may require additional scrubbing through a neutralizing or water-irrigated vent scrubber before final discharge

One recent atmospheric evaporator design has added a condenser and closed the air circuit to eliminate or minimize potential exhaust emissions. A much larger condenser is required to condense water vapor from a stream of air than would be required if air was not present. The presence of an inert gas, such as air, in the exhaust vapor stream reduces normal condensing coefficients by 90% or more.

An interesting application, which is well suited to atmospheric evaporation, involves the recovery and simultaneous cooling of hard chrome baths that often require external cooling to remove excess heat created by high operating amperage during plating.

In such circumstances, both rinsewater and bath may be blended for dewatering by the evaporator. In cases where the quantity of heat generated by the electric power demand of the bath is not adequate for the evaporation duty, the addition of external trim heat may be required.

Atmospheric evaporators are not considered to be energy efficient. At minimum, several pumps are required to introduce feed, to circulate the solution to be concentrated and, depending on system hydraulics, to remove concentrate. There are inherent inefficiencies in moving and heating large volumes of air. Spray temperatures must be high. Solution boiling points are higher at atmospheric pressure than under vacuum operation, which results in a lower effective temperature differential or thermal driving force.

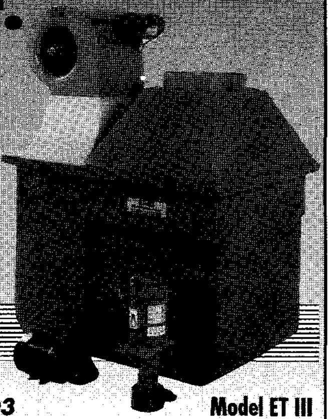
Despite the simplicity of design and lower initial capital cost, these factors conspire toward higher energy consumption, by an estimated factor of at least 10% beyond the theoretical requirement per pound of water evaporated when compared to single-stage vacuum evaporation. Vacuum evaporators have been used successfully for more than 30 years by the surface-finishing industry for point source recovery of plating baths and rinsewaters. They are somewhat more complex and require a higher initial capital investment than single-stage, noncondensing atmospheric units.

Vacuum evaporators are instrumented for push-button, fail-safe operation and provide close and consistent control of the recovered bath concentration.

There are three main categories of vacuum evaporator used in the surface-finishing industry to recover dragged out plating bath and rinsewater: (1) single-effect (single-stage) designs, which are usually the most simple and easy to operate (Fig. 3); (2) multiple-effect (multistage) designs, which are more complex but are more energy efficient; and (3) some special designs for such applications as brine concentration. All vacuum designs are devices for distilling a liquid phase at reduced temperatures in the absence of air and for producing a concentrate. Water distillate is also recovered as a by-product.

Vacuum evaporators, as employed by the plating industry for bath and rinsewater recovery, are usually the more simple, less complex, single-stage designs consisting of a


HAZARDOUS MATERIAL DISPOSAL
TOXIC WASTE



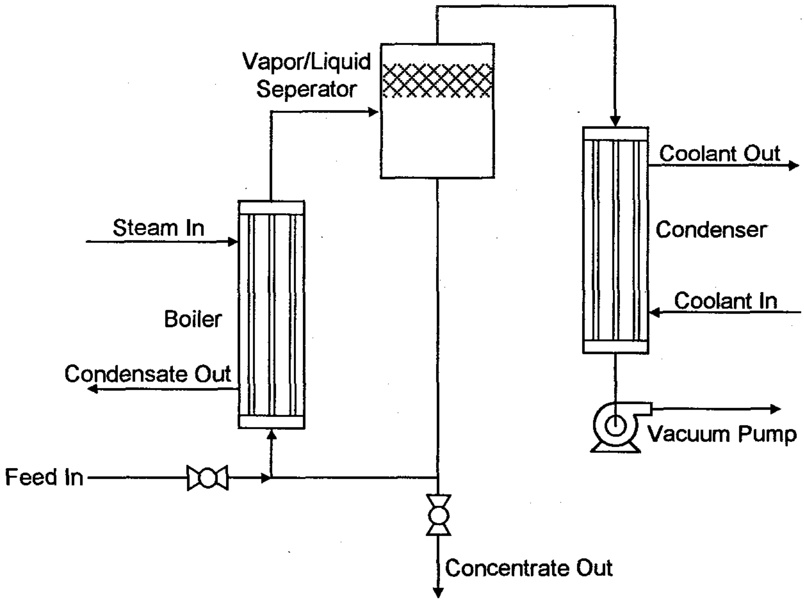
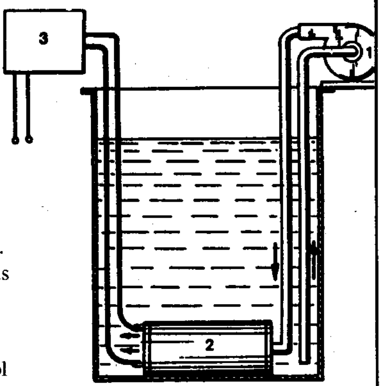


Fig. 3. Single-stage vacuum evaporation schematic.

heated boiler section, a vapor/liquid separator section, a water vapor condenser, a vacuum circuit, and a control system. The boiler and condenser sections may be arranged horizontally or vertically. The most common heating source is clean, low-pressure, saturated steam, which is ideal because it is a demand energy source and requires a minimum of control. When the supply pressure is regulated, the steam temperature is automatically established and does not require further control. Units are available to accommodate hot water and electrically driven heat pumps.

Some of the benefits of operating under vacuum are that it reduces the boiling temperature of the bath being concentrated, which lessens or eliminates the potential for thermal damage to heat-sensitive constituents or additives; increases the temperature differential (the thermal driving force) between the heat source and the liquid being concentrated resulting in smaller, more efficient and less costly boiler and condenser designs; extracts resident air from the system upon startup and eliminates any possibility of carry-over of hazardous chemicals to a vent stream; excludes air from the system, which eliminates the potential for air oxidation of recovered chemicals or bath; recovers high-quality water distillate for return to the plating line; desensitizes the system to fluctuations in feed concentration when operated in a concentrate recycle mode; eliminates the potential for hazardous air emissions; lessens the tendency for scale to form on heating or other surfaces by operating at reduced temperatures; provides better management of foam; reduces the number of pumps required to one, the vacuum pump or eductor circulating pump, whichever is used; and provides tight process control by recovering bath at an adjustable and repeatable concentration.

The operating vacuum selected or recommended by the evaporator supplier is generally a function of the chemistry of the particular bath being recovered. Baths containing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heat-sensitive constituents, such as expensive organic brighteners or additives, are usually concentrated under higher vacuum and lower boiling temperatures than are baths that do not require such constituents.

High vacuum operation requires physically larger evaporators to accommodate the higher specific vapor volumes encountered under those conditions and to maintain vapor velocities and system pressure drop within design ranges.

The level of vacuum, and thus the boiling point, can be varied within a specific range of vacuum for any given evaporator capacity. But, if an evaporator designed for optimum performance at 11 in. of mercury vacuum is operated below its design vacuum, say at 26 in. of mercury vacuum, vapor velocities will increase substantially and both the output capacity and product quality will deteriorate.

To satisfy the range of vacuum required by the widely differing bath chemistries used in the surface-finishing industry, suppliers of vacuum units have developed a series of standard, off-the-shelf, corrosion-resistant evaporator designs to accommodate most bath chemistries and operating requirements.

The energy demand of a single-stage vacuum evaporator is roughly 1,000 Btu/lb water evaporated, or roughly 9,000 Btu/gal of water evaporated (allowing for losses), the same as the theoretical energy requirement for atmospheric operation.

Because a high percentage of drag-out is usually returned with either atmospheric or vacuum evaporation, impurity removal and management may be required. Such purification techniques are well established. In the case of chrome baths, and thanks to the fact that chromium is present as an anionic complex, cation exchange or electropurification systems can be easily applied in a separate hydraulic loop around the rinse system to remove and control any cationic impurities that may accumulate. For chromium etch systems, electrolytic reoxidation of trivalent chromium or electropurification, should be considered. In this application, electropurification will produce less discharge than would a cation exchanger by its associated reagent waste stream.

Contaminant removal or purification techniques normally used with other baths, such as carbon filtration or dummying for nickel baths, membrane electrolysis for metal impurity control, or carbonate removal from cyanide baths, can continue to be applied to the process baths as required.

Vacuum evaporation has been successfully and dependably used for many years to recover a wide variety of plating baths including such difficult chemistries as encountered in chromic acid plating and chromic/sulfuric acid etch baths. Associated rinsewaters are also recovered for reuse in the plating process.

An application for vacuum evaporation of some increasing interest is brine concentration. In some localities, the discharge of pretreated metal-finishing effluent is being restricted because the effluent still has a high salt concentration. Salt is the unfortunate and unavoidable byproduct of chemical treatment of metal-bearing wastewater.

Usually, pretreated wastewater effluent is further processed by membrane systems to further separate and consolidate the mixed salt solution. The reject from this step can then be processed by any of several types of vacuum evaporator to concentrate the brine either to a level slightly below the limit of solubility of the salt mixture or slightly beyond to produce a concentrate discharge from which the salt slurry can settle and be discharged. The supernatant liquor can be returned to the feed circuit where it will mix with the incoming feed for reprocessing through the evaporator.

Reverse Osmosis

After evaporation, reverse osmosis (RO) has the longest operating history. Most commercial recovery installations have been on nickel plating operations.

On the positive side RO is a relatively mature technology and uses considerably less energy than evaporation for the same rinsewater feed rate. A typical recovery scheme is given in Figure 4.

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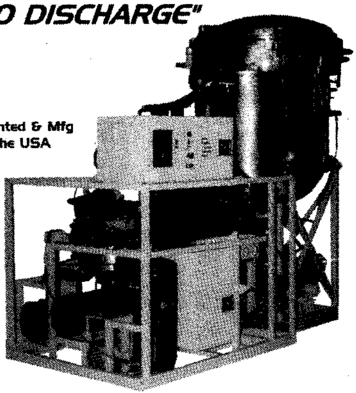

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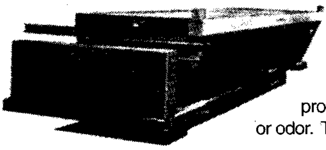

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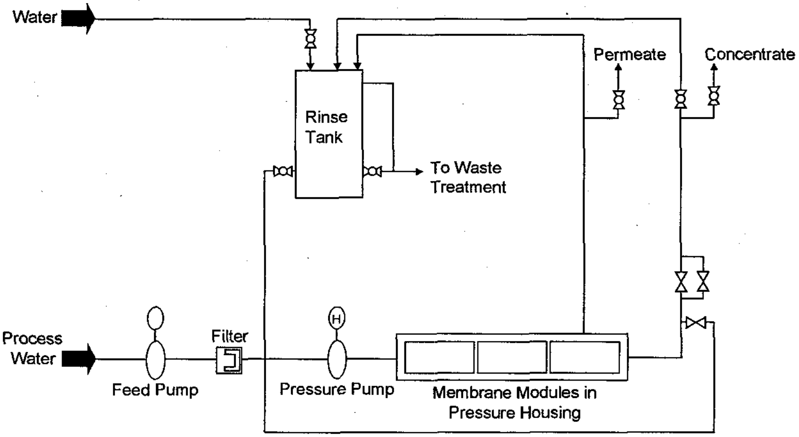


Fig. 4. Reverse osmosis flow schematic.

On the negative side, the degree of concentration of the separated bath by RO is limited. If maintaining appropriate permeate quality [10–100 ppm total dissolved solids (TDS)], the practical maximum concentration of the reject (or concentrate) is 10,000 ppm (1.4 oz/gal) TDS. If permeate quality is not an issue, then 50,000 to 80,000 ppm (6.7–10.7 oz/gal) TDS reject concentration can be achieved. In many cases, if the recovered solution is returned directly to the plating bath, there may not be sufficient natural water evaporation from the bath to accommodate the volume of recovered RO concentrate. Similar to evaporation, RO returns essentially all of the undesirable impurities.

RO has gained favor in recent years as a pretreatment for incoming process water, which has high TDS, and in some cases, for clean up of contaminated process water for recycle to the process.

RO is a pressure-driven membrane process. The driving force of this process, the hydrostatic pressure gradient, is the difference in hydrostatic pressure between two liquid phases separated by a membrane.

In reverse osmosis, particulates, macromolecules, and low molecular mass compounds, such as salts and sugars, are separated from a solvent, usually water. This is accomplished by applying a hydrostatic pressure greater than the osmotic pressure of the feed solution. The osmotic pressure of a particular feed solution varies directly with the concentration of the solution. In typical applications feed solution have a significant osmotic pressure, which must be overcome by the hydrostatic pressure applied as the driving force. This pressure requirement limits the practical application of this technology.

The transmembrane flux (permeate flow) is a function of hydrodynamic permeability and the net pressure difference—the hydrostatic pressure difference between feed and filtrate solutions minus the difference in osmotic pressure between these solutions. The osmotic pressure of a solution containing low molecular mass solutes can be rather high, even at relatively low solution concentrations.

In practice, it is practical to use RO to separate water (solvent) from all other substances of a solution in order to concentrate the solution and/or to generate or recover clean water for process reuse. The applied pressure is generally between 200 and 700 psig. In some cases, such as advanced reverse osmosis and high-pressure applications, the pressure may be as high as 1,000 to 2,000 psig.

Depending on both the characteristics of the dissolved constituents and on the practical operation of the equipment, the dissolved constituents are rejected differently. This phenomenon is called the membrane rejection rate. The fraction of nonrejected substances is called leakage. The leakage of the various salts is dependent on the following parameters: size of dissolved molecules, ion radius electrical load of the ions, and interacting forces between ions and solvents.

The rejection of organic substances is mainly dependent on the molecular weight and size of the molecules.

RO has seen limited application to nickel rinsewater. RO can separate and return clean nickel bath, but usually at too low a concentration for total return to the process bath. Also, with RO, boric acid is partially transported across the membrane requiring monitoring and make-up as required.

Membrane performance decreases with operating time resulting in a decreased permeate flow rate (flux), which can be reasonably restored by periodic cleaning of the membrane. Over time, the membranes will likely require replacement due to damage from (1) hard water constituents; (2) fouling by organics; (3) general deterioration by acids or alkalis; (4) normal membrane compaction with use; and (5) destruction by oxidizing chemicals such as peroxides, hypochlorite, or chromic acid.

Electrodialysis

Electrodialysis (ED) uses a "stack" of closely spaced ion exchange membranes through which ionic components of a solution are selectively transported. The driving force is a rectifier-generated voltage imposed on electrodes at the two ends of the stack. Ionic components are pulled out of a relatively dilute rinse stream (the first flowing rinse station) and accumulated in a highly concentrated stream, which can be either returned to the process, as shown in Figure 5, or otherwise recovered.

The advantages of ED include low energy consumption, the ability to produce a highly concentrated stream for recovery, and the fact that only ionic materials are recovered, so that many undesirable impurities are retarded and rejected. On the negative side, ED is a membrane process, which requires clean feed, careful operation, and periodic maintenance to avoid damage to the stack, which is usually reconditioned by the manufacturer when required. ED units can be successfully used to recover gold, silver, nickel, and tin electrolytes as well as selected acids and rinsewater.

An interesting feature of this technology is that a bright nickel electroplating bath can be circulated at a slow rate through the unit, thus providing a continuous removal of organic impurities, essentially eliminating the need for batch purification with its associated major losses of nickel metal.

Membrane Electrolysis

Membrane electrolysis (ME) is a membrane process driven by an electrolytic potential. It is mainly used to remove metallic impurities from plating, anodizing, etching, stripping, and other metal-finishing process solutions. This technology utilizes a diaphragm or an ion exchange membrane and an electrical potential applied across the diaphragm or membrane. Compared to electrodialysis, most membrane electrolysis systems utilize only a single membrane or diaphragm positioned between two electrodes.

The use of ion exchange membranes is advantageous because higher ion transfer rates can be achieved in comparison to inorganic- or organic-based diaphragms. Ion exchange membranes are ion permeable and selective, permitting ions of a given electrical charge to pass through. Cation exchange membranes allow only cations, such as copper or aluminum, to pass through. Similarly, anion exchange membranes allow only anions, such as sulfates or chlorides, to pass through.

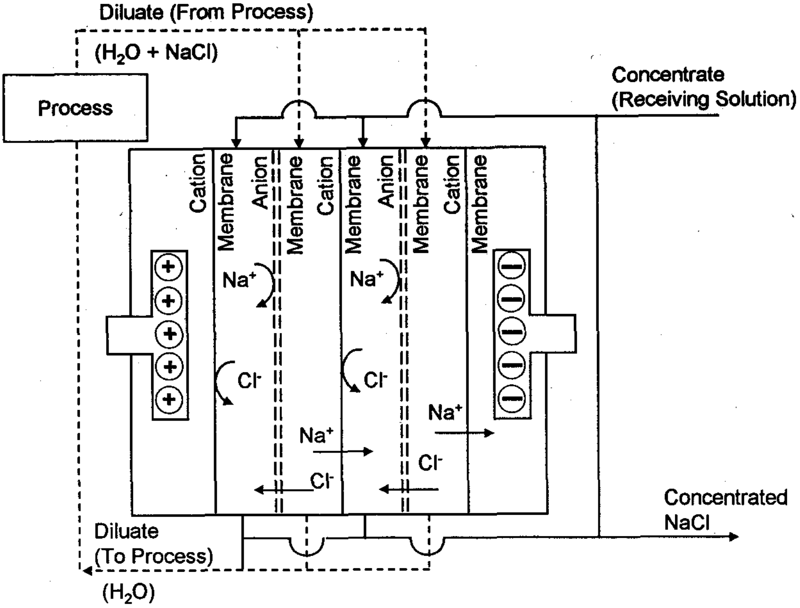


Fig. 5. Electrodialysis flow schematic.

The efficiency of ME depends on the migration rate of ions through the ion exchange membranes. The energy required is the sum of two terms: (1) the electrical energy required to transfer the ionic components from one solution through the membrane into another solution, and (2) the energy required to pump the solutions through the unit.

Electrochemical reactions at the electrodes are other energy-consuming processes, but the energy consumed for electrode reactions is generally less than 1.0% of the total energy used for ion transfer.

The total electrical potential drop across an ME cell includes the concentration polarization and the electrical potential required to overcome the electrical resistance of the cell itself. This resistance is caused by the friction between ions, membranes, and water during transfer from one solution to another, all of which results in an irreversible energy dissipation in the form of heat. Because of the heat generated, the total energy required in practice is significantly higher than the theoretical minimum energy required.

The energy necessary to remove metals from a solution is directly proportional to the total current flowing through the cell and the voltage drop between the two electrodes. The electric current required to remove metals from a solution is directly proportional to the number of ions transferred through the ion exchange membrane from the anolyte to the catholyte. The electrical energy required in ME is directly proportional to the quantity of metal (cations) that must be removed from a certain volume of anolyte to achieve the desired product quality.

Energy consumption is also a function of the electrical resistance of a cell pair. The electrical resistance of a cell pair is a function of the individual resistances of the membrane and the solution in the cell. Furthermore, because the resistance of the solution is directly proportional to its ionic concentration, the overall resistance of a cell is usually determined by the resistance of the weaker electrolyte. Figure 6 is a schematic of the ME cell.

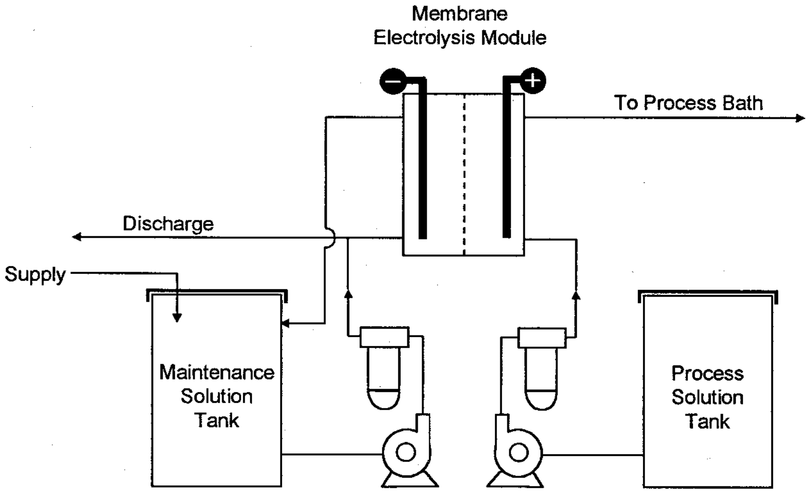


Fig. 6. Membrane electrolysis system schematic.

ME can be utilized to remove metal impurities from process baths, such as etch and stripping baths, as well as conversion coating, chemical milling, and sealing solutions. An effective membrane surface area between anolyte or process solution and catholyte of 0.07 m^2 or 0.75 ft^2 allows a maximum amperage of 60 to 100 A for process solution purification. This membrane electrolysis process does not only remove metals from process solutions but also helps to maintain these solutions at certain activity levels.

When applied for the purification of a very corrosive solution that can dissolve metal electrodes, a three-compartment ME system must be used. A center compartment is utilized for the corrosive process solution and the adjacent compartments, which are separated by ion exchange membranes from the center compartment, operate as catholyte and anolyte compartments. During operation, anolyte/catholyte-maintenance solutions are recirculated through their corresponding cells and storage tanks. The purified process solution is pumped via a designated pump from the process tank back into the process bath.

Depending on the chemistry and the specific application, ME systems are designed either with cation or with anion exchange membranes. Typical applications for the ME technology in surface-finishing operations include regeneration of etching and stripping solutions; purification and regeneration of chromium plating baths; recycling and maintenance of chrome conversion coating solutions; and reactivation and metal removal from deoxidizing solutions.

Benefits of the ME technology are consistent performance and quality of etching agents and acids; constant production speed; accurate high-quality etching and chrome conversion coating results; reduced reject rate (no costly refinishing) reduced manpower requirement because of process automation; and reduced wastewater treatment and waste disposal result in lower operating cost.

Diffusion Dialysis

Diffusion Dialysis (DD) is also a membrane technology for separating and recovering clean acid from used or spent acid solutions. Compared to electrodialysis or ME, DD does not require an electrical potential across the membrane to effect separation. A flow schematic of a typical DD system is illustrated in Figure 7.

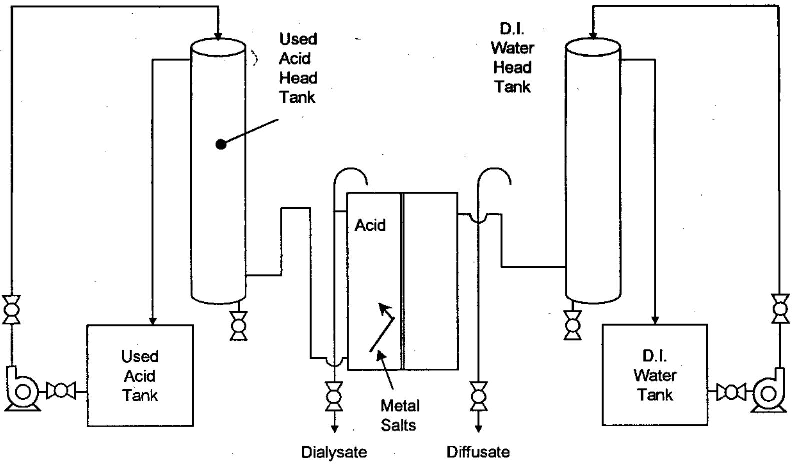


Fig. 7. Diffusion dialysis system schematic.

The separation mechanism utilizes the concentration gradient between two liquids—deionized (DI) water and the used process acid—separated by a specific anion exchange membrane, which allows natural diffusion of highly dissociated acid (anions) through the polymeric membrane structure while cations (metals) are rejected because of their positive electrical charge. The mechanism of free acid diffusion through the membrane, due to the concentration difference between the free acid and DI water, is known as Donnan diffusion.

Multiple layers of membrane are arranged in a filter-press-like stack through which both DI water and spent acid flow by gravity. Clean acid is separated from the feed stream by the concentration-driven transport mechanism across the membrane stack to effect a partition and recovery of an acid stream (diffusate) in conjunction with the generation and discharge of a waste stream (dialysate).

DD is being utilized for the following applications: recycle of hydrofluoric/nitric acids for etching stainless steel; recovery of sulfuric/nitric and sulfuric/hydrochloric acids for etching nonferrous metal; reclamation of sulfuric and hydrochloric acids for etching of steel-based materials; recuperation of sulfuric acid from anodizing processes; and regeneration of battery acids.

On the positive side DD is a low-energy, low-pressure, continuous process that requires no additional reagent or regeneration chemicals, resulting in less TDS in the plant discharges.

On the negative side, for every volume of acid recovered (diffusate), an equal volume of acidic waste (dialysate) is generated for further processing for recovery or for waste treatment. While the recovered, clean acid is generally reusable, the operating principle imposes a limit to the achievable concentration for the recovered acid, which can be fortified with concentrated acid as required.

Typical maintenance procedures for DD systems include: filtration of the feed stream to remove total suspended solids and to avoid deposition of suspended solids on the membranes; temperature regulation of the feed liquor and DI water supply within a prescribed temperature range to maintain recovery efficiency; and protection of the membranes against exposure to oxidizing agents such as chromic and nitric acids and to organic solvents, lubricants, inhibitors and surfactants.

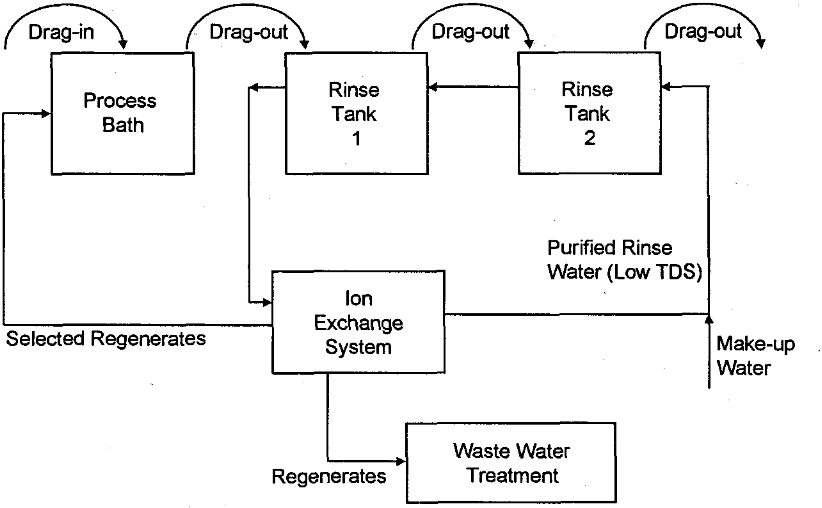


Fig. 8. Ion exchange schematic.

With efficient feed filtration, membrane cleaning is generally required approximately twice per year. With observance of the above operating and maintenance practices, experience indicates membrane life can be about 5 years.

Ion Exchange

Ion exchange is a chemically driven separation process. It is an ideal and useful separation method for collecting low concentrations of ionic materials, such as metal salts, from dilute rinsewater. This characteristic differentiates it from all of the previously discussed methods where relatively low flow rates and high concentrations of recoverable materials must be maintained.

From a recovery standpoint, ion exchange is not capable of producing a "highly" concentrated stream for recycle (20–25 g/L is a practical limit). It is also difficult to optimize the split between recovered metal salts and excess regenerant acid, which is intolerable in the plating bath. Also noteworthy is the fact that a waste stream containing excess regenerant must be dealt with, as shown in Figure 8.

NONRECOVERY METHODS

Nonrecovery or indirect recovery methods do not return concentrate to the originating process; thus, they obviate any concern over accumulation of impurities or the primary metal in the bath. The result is a "decoupling" of the recovery process from the basic manufacturing operation, which may be a considerable benefit if downtime or process upsets cannot be tolerated. A general schematic is given in Figure 9.

In certain instances, these nonreturn processes may also allow recovery from process bath losses other than drag-out (i.e., purification losses or plating bath desludging waste). This is in sharp contrast to the previous category of recovery methods, which can actually increase losses to purification or sludge removal operations by increasing the frequency with which they must be performed.

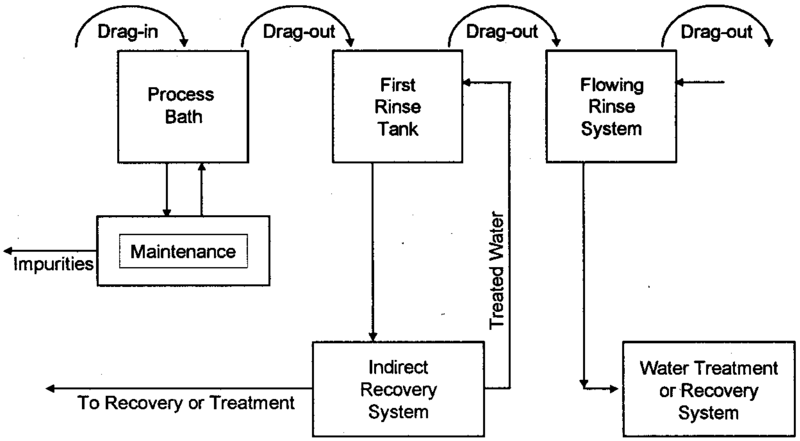


Fig. 9. General schematic for nonrecovery or indirect recovery methods.

Electrolytic Metal Recovery

In the metal-finishing industry electrolytic metal recovery (EMR) is both a useful and a familiar electrochemical process technique that applies special electroplating equipment to reduce the concentration of dissolved metals in many types of process solutions such as plating rinse water and dumped baths. Removing metal in solid form avoids the need to treat and convert the metal content of such process solutions to sludge. In the mining industry, EMR is referred to as electrowinning.

Recent advances in EMR cell design now make it possible to reduce the metal concentration of spent electroless baths and rinsewater prior to waste treatment and to recover metal from chloride or ammoniacal etch solutions while concurrently regenerating the etch baths.

There are three common embodiments of EMR in commercial use in the plating industry:

1. "Extractive" methods, which aim primarily to remove the metal from the recovery rinse but with little regard to byproduct value, are depicted in Figure 10. One of these deposits the metal on a sacrificial plastic starter cathode. The cost of the starter cathode and the undesirability of introducing plastic to a smelter or secondary recovery operation are a significant offset to any resale value of the metal.

   Another type of extractive cell produces a spongy or powdery deposit, which is removed as a sludgelike material (usually from the bottom of the recovery cell) and is usually of little or no value. The high surface area of the powder exposes a significant portion of the metal to oxidation. The powder also entrains mother liquor, which is virtually impossible to rinse out completely. This results in an acidic, wet powder, often contaminated with halite ions, which in turn render the recovered metal powder difficult or impossible to reuse or sell.
2. High-surface-area recovery cells deposit the metal on some type of fibrous or filamentous substrate. In some cases, the plated metal is discarded or sold as a low-volume residue, while in others, the deposited metal is stripped chemically or electrochemically so that the end result is a concentrated solution of the metal that was recovered.
3. True EMR or electrowinning approaches recover a solid slab or sheet of relatively high-purity metal, that can be easily handled, weighed, assayed, or transported and

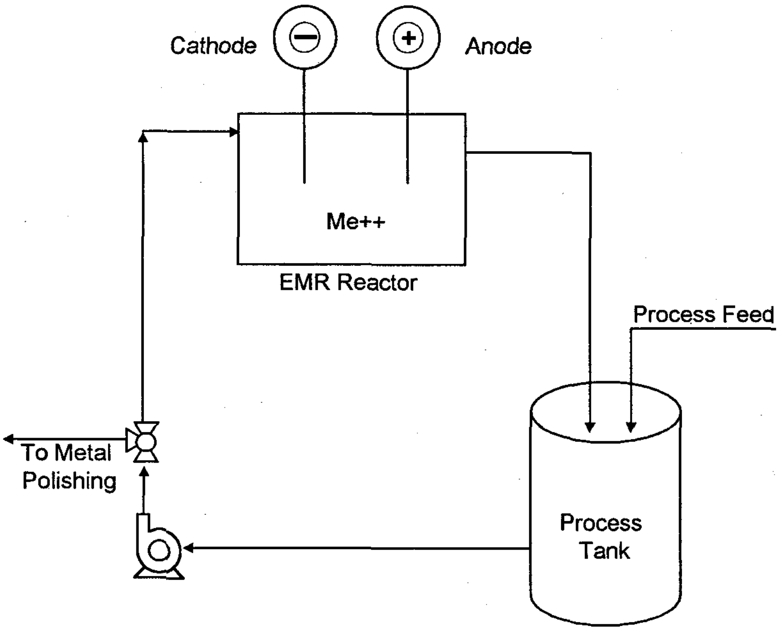


Fig. 10. Electrolytic metal recovery schematic.

sold for the best available price in the secondary metal markets. In certain recovery applications or circumstances, the electrodeposited metal is pure enough to be reused as anode material in the originating plating process. This type of cell usually applies some type of moving or rotating cathode, or alternatively, a high solution velocity over fixed cathodes.

To reduce the effect of electrode polarization common to low metal ion concentrations and to increase ion diffusion rates at the electrodes, it is recommended the solution be heated. Otherwise, plate-out of metal from these low concentration solutions will be hindered. Strong air agitation is another method for providing adequate mechanical mixing, but it removes heat from the system, thus reducing operating rates. Air agitation may also add to the load on air pollution control equipment.

Ion Exchange

In addition to the use discussed earlier under concentrate recovery methods, ion exchange can be used for several other applications, which include recuperation of noble metals, recovery of metals from rinsewater in combination with electrolytic metal recovery, and the purification of some process solutions such as chromate baths.

In gold recovery, ion exchange is effective in collecting essentially at traces from a dilute rinse stream. Historically, such gold-laden ion exchange resins were burned by a gold refiner who recovered the ash. Currently some companies are offering a tolling service to regenerate the ion exchange resin chemically and return it to the user.

In either case the primary disadvantages are the difficulty in assaying a heterogeneous

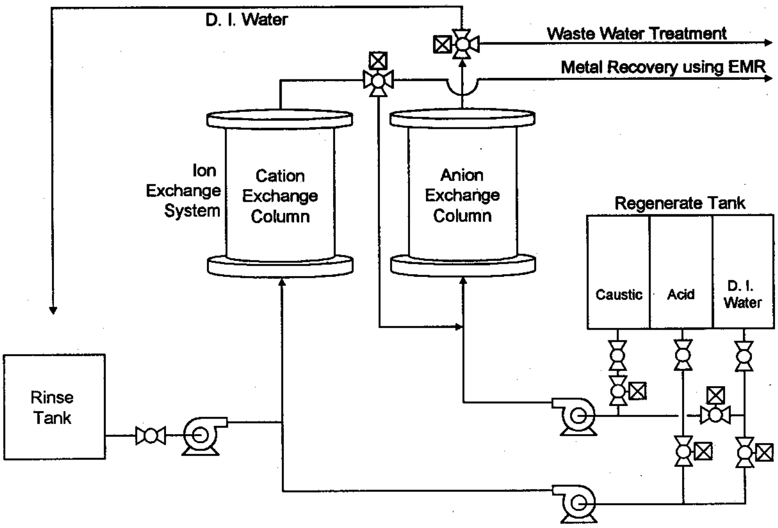


Fig. 11. Combined ion exchange and electrolytic metal recovery system schematic.

mass of metal-laden ion exchange beads and the high tolling charges from the refiner or processor. Both of these factors preclude recovery of maximum gold value.

A second emerging application involves linking two recovery techniques; ion exchange and EMR. In this scheme, as shown in Figure 11, the ion exchange bed is used to collect metal ions from dilute rinsewater and the acid formed in the electrowinning operation serves to regenerate the ion exchange resin.

SLUDGES AS BYPRODUCTS

There has been a steady increase in the number of companies interested in using metal-bearing waste treatment sludge as a feedstock in their manufacturing processes; nevertheless, most mixed sludge has no value. In fact, the generator often has to pay freight costs plus a fee to the processor for removal and treatment. A typical example would be a sludge containing 5 to 10% copper or nickel, which can be used as a feedstock for a pyrometallurgical operation (a smelter). Such metal-finishing sludge is a richer source of feedstock than the typical ore mined from the ground.

On the other hand metal-finishing sludge is typically highly variable in composition and can contain a significant amount of inorganic salt in the entrained water. Halides can be particularly troublesome in a smelting operation. From the standpoint of long-term liability, the metal finisher needs to consider that 90 to 95% of such sludge will not be turned into product at the smelter but will wind up in the smelter's residues. Although such recycling may appear advantageous under today's regulations, the long-term environmental significance of smelter residue needs to be factored into the decision.

A more promising situation exists if a metal finisher generates a segregated sludge that consists essentially of a single metal. Single metal sludges containing only tin, nickel, cadmium, copper, or zinc have excellent potential for being used as feedstock for reclaiming operations, which can operate in an environmentally "clean" manner, producing little or no residue.

Furthermore, the metal content of such segregated sludge may be a candidate for in-house recovery by the metal finisher by redissolving the sludge and applying EMR. Segregated sludge is the natural by-product of the closed-loop or integrated rinse treatment method, which has been successfully practiced for decades in both the U.S. and Europe.

REGENERATION OF BATHS

Historically, most of the effort on recovery was focused on drag-out; however, most of the chemical load from a metal-finishing operation will usually be found in the dumps of expendable process baths and the losses from purification of plating solutions or sludge removal of the process tank. Operations, such as cleaning, pickling, bright dipping, etching, and chemical milling, are worth being investigated for recovery potential. Some of these applications are discussed in the following.

Copper and Its Alloys

EMR as described earlier is highly effective on many copper pickling and milling solutions including sulfuric acid, cupric chloride, and ammonium chloride solutions. Solutions based on hydrogen peroxide are generally best regenerated by crystallization and removal of copper sulfate with the crystals being sold as a byproduct or redissolved for EMR.

Bright dipping in highly concentrated nitric/sulfuric acid is a difficult challenge for regeneration because the solution volumes involved are usually quite small (5–25 gal) and the drag-out losses are very high. Regeneration is theoretically possible by distillation of the nitric acid and removal of copper sulfate but the economics are not likely to be attractive for most metal finishers. This approach does have potential for larger plating plants or for large-scale, centralized recovery facilities, which serve a number of plants.

Aluminum and Its Alloys

The caustic etch used in many aluminum finishing lines and the chemical milling solution used for aircraft components can be regenerated by crystallization and removal of aluminum trihydrate; however, the process must be carefully controlled and maintained. The economics currently favor only relatively large installations but development of lower cost approaches is likely.

Sulfuric acid anodize solution and phosphoric acid bright dip bath can both be regenerated using DD or acid retardation, which is a sorption process using ion exchange resins. The cost and complexity of such recovery operations require economic evaluation on a case by case basis.

Chromic acid anodizing solutions can be regenerated by the use of cation exchange or ME. Both technologies can be used to remove the accumulating aluminum together with other metal impurities such as copper and zinc. The life expectancy of the resin is shorter than on normal waste treatment applications, but the method is still practical and economical. The use of ME has shown effective purification and maintenance capabilities of these baths.

Iron and Steel

Pickling is commonly used in steel mills for the surface finishing of steel products or as a pretreatment operation for a galvanizing process. Large volumes of spent acid containing metal contaminants are generated. Among the various methods available for acid purification and recovery, DD is very useful for the recovery of free acid from spent pickling baths.

Both sulfuric and hydrochloric acids are commonly used for cleaning steel. Sulfuric acid can be regenerated by crystallization of ferrous sulfate. Hydrochloric acid can be recovered by distilling off the acid and leaving behind the iron oxide. These technologies have been used for many years in large installations and by tolling reclaimers but are not likely to ever be economical for small metal-finishing or galvanizing plants where the production cannot justify the capital investment.

Plastic Etching

Concentrated chromic acid solutions are used to etch plastic surfaces prior to plating. These operations consume very high quantities of chemicals and generate large quantities of sludge. Standard practice today is to reclaim essentially all of the chromium from such an operation through a combination of evaporation and electrochemical oxidation of the trivalent chromium.

Today, a combination of evaporation and ME can be used to extend the operating time of a chromic acid etch indefinitely.

Alkaline Cleaners

Alkaline cleaners are probably the most widely used process baths in all of metal finishing. Treatment significance will increase as water recycling becomes a more prevalent practice. Most cleaner formulations are antagonistic to good treatment of a metal-finishing effluent because they are chemically formulated to keep dirt and oil in suspension. If their concentration is high enough in an effluent this same effect prevents efficient removal of the precipitated metals.

Dumps of alkaline cleaners, passing through a treatment system, are a notorious source of upsets and a high contributor to the TDS in a metal-finishing effluent. In addition there are certain cases where large finishing operations on small sewer systems, or small receiving streams, may have a problem meeting requirements for the organic content due to wetting agents and detergents.

The cleaning of parts in surface-finishing operations generates a lot of impurities in the cleaner bath. These impurities, such as oils, dirt, and soil, wear out the cleaner baths and have to be removed to extend the life of the cleaner. Free or tramp oil is usually removed with a skimmer. Emulsified oil will usually build up in the bath, with some of it splitting into a floating layer where it will be removed by the skimmer. Most of the aqueous and semiaqueous bath formulations contain an inhibitor to provide rust protection for steel parts. Surfactants displace oil from the parts to be cleaned and form a stable emulsion. The life of the bath is dependent upon how much soil is brought in with the parts and how much drag-out occurs as the parts are moved from the cleaning bath into the rinse tank.

For many installations in surface-finishing operations continuous micro- and ultrafiltration systems using inorganic or organic membranes are successfully used to remove oils, grease, lubricants, soils, and solids from alkaline cleaners and can give the bath essentially indefinite life. An additional benefit is the steady-state condition of the cleaner, which will improve control over the process and the quality of the product being manufactured. The selection of the membranes is not only important regarding the operating temperature of the bath but also for the pore size or macromolecular structure. Elevated temperature can deteriorate organic-based membranes and too small a pore size can cause the rejection of valuable chemicals such as surfactants or inhibitors.

Phosphating Baths

Precipitates are formed continuously in phosphating operations presenting maintenance headaches and often resulting in the solution being discarded. Usually, the precipitates accumulate in the process tank, primarily on the heating coils.

When the solution is removed from the tank this accumulation of sludge can be manually removed. The solution should be decanted back into the tank to minimize wastage but this consumes space and time so the solution is often discarded and replaced.

It is far more efficient to install a continuous recirculation system through a clarifier with gentle agitation in the sludge blanket zone. This allows the solution to be used indefinitely, reduces the labor for manual clean-out of sludge, and allows a dewatered sludge to be easily removed from the bottom of the clarifier.

Chromating Solutions

Both ion exchange and electrochemical methods have been demonstrated to be effective for regeneration of spent chromates; however, in almost all cases, the metal finisher relies upon the proprietary chemical supplier to be responsible for the appropriate balance in the chromating bath. Either of these regenerating technologies makes the metal finisher responsible for the overall chemical maintenance of all constituents in the bath. It is possible that proprietary suppliers will provide a service to assist the finisher in maintaining a proper balance when one of the applicable techniques is applied. Economics are not likely to be attractive except in the case of high production operations using the more concentrated chromates, which give high salt spray resistance against "white rust."

RECOVERY AND RECYCLING OF PRETREATED WASTEWATER

Conventional techniques for water conservation (countercurrent rinsing, conductivity controls, etc.) are used extensively in the industry; however, the unavoidable end product of all waste treatment methodologies is a "salt" containing effluent, or brine. Effluent TDS from such a system can be sufficiently high to limit potential for recycle and reuse as process water without desalination.

Clearly, achieving the minimum consumption and discharge of water necessitates segregated handling of concentrated solution dumps since they will carry more TDS over a given period of time than bath drag-out. In a similar fashion the use of segregated closed-loop treatment rinses allows the first station of the rinse system (drag-out tank) to be as high as 10 to 15% of the TDS of the process bath, greatly extending the opportunity to recycle subsequent higher quality rinses.

There is increasing interest in this country to further close the loop by desalinating a treated effluent for maximum recycle and reuse. A number of large plants have been constructed with all of the TDS being concentrated into a small volume of brine, which is hauled from the plant.

While this may be necessary and economical in some cases it is not logical for most cases. Unless the plant is located near a seacoast, disposal of the brine is likely to be problematic. It is highly corrosive to concrete and steel structures and more difficult to assimilate in the environment than a high volume effluent at 1,000 mg/L TDS. The real answer lies in reducing the consumption of chemicals in the metal-finishing operation and thus the quantity of TDS requiring discharge.

For situations where desalination and recycling of a treated effluent is desirable or necessary the following treatment technologies can be considered.

Ion Exchange

Recycling of metal-finishing wastewater through ion exchange equipment has been practiced for decades in Germany and for many years in Japan. Practical experience shows the need for segregated collection and treatment of not only batch dumps but also the first rinse after each process that flows at a rate to take away approximately 90% of the chemical load.

Secondary and/or tertiary rinses can then be recirculated through ion exchange equipment after very thorough particulate filtration and carbon filtration. Cyanide and hexavalent chromium are problematic because they are poorly released from the anion exchange resins and tend to exist as perpetual low-level contaminants throughout the plant's rinsewater system.

Aside from high cost, the major drawback of this approach is that it actually increases the TDS discharge from the plant. In theory, if regeneration of ion exchange resins could be perfectly efficient, the process would multiply the TDS removed from the recirculated water by a factor of two. In practice, however, a 100 to 300% excess of regenerant chemical is typically required. This can be reduced to the range of 50 to 100% excess by holding and reusing certain fractions of the regenerant waste stream at the cost of additional capital investment and operating complexity. As a result of this need for excess regenerant, the TDS removed from the recirculating rinsewater is multiplied by a factor of three to six.

Since it is the TDS that presents the problem for the environment and not the water, this approach does not hold long-term promise for the metal-finishing industry. In Germany, the population density has exacerbated the problem with TDS accumulating in the rivers. Practicing water chemists now recognize the counterproductive nature of this treatment process.

Evaporation/Distillation

Where either waste heat or reliable solar energy are available, vacuum evaporation or multistage vacuum distillation can be an attractive alternative for producing clean water. Capital costs are high but the ability to concentrate the brine is virtually unlimited and the equipment is rugged and reliable.

Reverse Osmosis

RO technology has been refined and extensively applied to the desalination of sea water and brackish waters. Metal-finishing wastewater requires a relatively high degree of pretreatment and filtration to protect RO membranes from fouling. Pretreatment processes can be designed so that soluble compounds, such as metal silicates and oxides, can be removed as precipitates by a filtration stage to such a high degree that membrane fouling can be significantly avoided; however, because of the wide variety of chemicals used in metal finishing, the water chemistry can be complex, highly variable over time, and difficult to accurately predict.

The large commercial scale installations have had mixed results. Success on one plant effluent is not assurance that the next will be workable. In addition the concentration of brine that can be produced is relatively low so that large quantities of low-concentration brine require disposal.

Electrodialysis

ED has also found extensive commercial applications for desalination of brackish water; however, the efficiency of the process falls off unacceptably if the product water is not in the range of 500 to 600 mg/L TDS or higher. The process can produce a rather high concentration of brine and the water quality limitation can be overcome by using RO or ion exchange for high purity applications within the plant.

Since ED is also a membrane process, similar concerns apply as mentioned for RO; however, ED is likely to prove somewhat more tolerant of varying water chemistry. This is due to the ability to frequently reverse the electrical potential across the membrane stack, which helps offset the fouling tendency, albeit at a sacrifice in capacity.

Zero Liquid Discharge Systems

Some firms, because of their location in small towns with small municipal treatment plants or because of discharge restrictions or other circumstances, have implemented treatment and recovery programs geared to recover all possible process water for recycle and reuse within the plant. Only solid sludge or brine slurry is produced for haul-away and disposal. These firms come as close as practical to having a zero discharge operation.

While any of the foregoing methods can be applied individually to condition raw water, the recovery and conditioning of pretreated effluent requires a multistep process. It is not uncommon for a pretreated effluent to still have high TDS, mostly as sodium sulfate or sodium chloride. Some firms have successfully applied all or some of the following process steps to further process pretreated, high-TDS effluent to recover clean, reusable process water and to achieve zero liquid discharge: sand filtration, carbon filtration, single- or two-stage RO followed by mixed bed ion exchange (if necessary).

The reject from the RO system, which may still represent a considerable volume of dilute brine, can be further processed by vacuum evaporation to achieve a concentration close to the limit of solubility of the brine mixture, which is discharged from the evaporator at an elevated temperature. Upon cooling, salt crystals will separate and settle. The supernatant liquor can be mixed with the RO reject feed stream and circulated back through the evaporator. Meanwhile, the resulting salt slurry can be removed from the settling tank for further dewatering, which is not usually necessary, and readied for haul-away.

A process of this nature is probably not economically viable unless the total daily volume of process water used in the plant is in the order of 50,000 gpd or more.

APPENDIX

FEDERAL AND MILITARY SPECIFICATIONS

The following listing has been compiled from the latest available edition of the Department of Defense Index of Specifications and Standards (DODISS), which includes unclassified Federal and Military specifications, standards, and related documents as well as nongovernment standards adopted for DOD use.

Federal standardization documents and military documents are available for reference at General Service Administration Business Service Centers and some Federal Government Depository Libraries. Copies are available from: Federal Supply Service Bureau Specs Section (3FPB-W), Suite 8100, Washington, DC 20407.

Requests are handled through an automated system called the Acquistion Streamlining and Standardization System (ASSIST), Customer Accounting Management System (CAMS). ASSIST stores most documents as digital files in Portable Document Format (PDF). As requests are received, the appropriate document files are retrieved from the repository and printed, copied to diskette, or CD-ROM packaged and then shipped. Include your assigned customer number (one will be assigned for your first order); indicate your complete address; and list each desired specification or standard by document identifier, e.g., MIL STD. Document titles are helpful but not required. Allow one to two weeks for shipping of documents.

Standardization documents can also be ordered via the World Wide Web using ASSIST Shopping Wizard, managed by the DODSSP, Philadelphia. The ASSIST Shopping Wizard is available to all users having registered for an account. Account holders are given a password to access the system (www.dodssp.daps.mil). Further details and information are available from: DODSSP Special Assistance Desk, 700 Robbins Avenue, Bldg. 4D, Philadelphia, PA 19111-5094 (215-697-2179).

Services for obtaining documents by return fax or overnight are available commercially on a fee-paid basis.

Nongovernment standards are available from the sponsoring organization. The addresses are as follows:

For items designated AAMA:
American Architectural Manufacturers Association (AAMA)
1827 Walden Office Square, Ste. 104
Schaumberg, IL 60173
847/303-5664; fax, 847/303-5774

For items designated AMS:
Society of Automotive Engineers (SAE)
400 Commonwealth Dr.
Warrendale, PA 15096-0001 412/772-7129; fax, 412/776-2103

For items designated ASTM:
American Society for Testing and Materials (ASTM)
100 Barr Harbor Dr.
W. Conshohocken, PA 19428-2959
610/832-9500; fax, 610/832-9555

ELECTRODEPOSITED COATINGS

Cadmium and Cadmium Alloys

Cadmium Plating, Low Embrittlement, Electrodeposition—MIl-STD-870B
Electrodeposited Coatings of Cadmium—ASTM B 766-86
Cadmium-Titanium Plating, Low Embrittlement, Electrodeposition—MIL-STD-1500B
Plating, Cadmium—AMS 2400S
Plating, Cadmium (Electrodeposited)—QQ-P-416F
Plating, Cadmium, Low Hydrogen Content Deposit—AMS 2401D
Plating, Cadmium-Titanium—AMS 2419A-79

Chromium and Chromium Alloys

Chromium Electroplating on Steel for Engineering Use—ASTM B 177-93
Chromium Plating (Electrodeposited)—QQ-C-320B
Chromium Plating, Hard Deposit—AMS 2406G
Chromium Plating, Black (Electrodeposited)—MIL-C-14538C
Chromium Plating, Electrodeposited—MIL-C-23422E
Chromium Plating, Electrodeposited, Porous—MIL-C-20218F
Chromium Plating, Low Embrittlement, Electrodeposition—MIL-STD-1501C
Electrodeposited Coating of Copper Plus Nickel Plus Chromium and Nickel Plus Chromium—ASTM B 456-94
Electrodeposited Engineering Chromium Coatings on Ferrous Substrates—ASTM B 650-95

Copper

Copper Plating—AMS 2418D
Copper Plating (Electrodeposited)—MIL-C-14550B
Electrodeposited Coating of Copper Plus Nickel Plus Chromium and Nickel Plus Chromium—ASTM B 456-94
Electrodeposited Copper for Engineering Uses—ASTM B 734-84

Gold

Electrodeposited Coatings of Gold for Engineering Uses—ASTM B 488-95
Gold Plating - for Thermal Control—AMS 2425D
Gold Plating, Electrodeposited—MIL-G-45204C

Indium

Lead and Indium Plating—AMS 2415F

Lead and Lead Alloys

Electrodeposited Coatings of Lead and Lead-Tin Alloys on Steel and Ferrous Alloys—ASTM B 200-85
Lead and Indium Plating—AMS 2415F
Lead Plating (Electrodeposited)—MIL-L-13808B
Lead-Tin Alloy Coating (Electrodeposited)—MIL-L-46064A

Nickel and Nickel Alloys

Electroplated Engineering Nickel Coatings—ASTM B 689-90
Measurement of Coating Thicknesses by the Magnetic Method: Electrodeposited Nickel Coatings on Magnetic and Nonmagnetic Substrates—ASTM B 530-88
Nickel Plating (Electrodeposited)—QQ-N-290A
Nickel Plating, Low Embrittlement, Electrodeposition—MIL-STD-868A
Nickel-Cadmium Plating, Diffused—AMS 2416G

Plating, Black Nickel (Electrodeposited) on Brass, Bronze, or Steel—MIL-P-18317
Plating, Nickel, General Purpose—AMS 2403J
Plating, Nickel, Low Stressed Deposit—AMS 2424D
Plating, Soft Nickel (Electrodeposited), Sulfamate Bath—MIL-P-27418

Palladium

Electrodeposited Coatings of Palladium for Engineering Use—ASTM B 679-91
Palladium Plating (Electrodeposited)—MIL-P-45209B

Rhodium

Electrodeposited Coatings of Rhodium for Engineering Use—ASTM B 634-88
Silver and Rhodium Plating—AMS 2413C

Silver

Electrodeposited Coatings of Silver for Engineering Use—ASTM B 700-90
Plating, Silver, Nickel Strike, High Bake—AMS 2410H
Silver and Rhodium Plating—AMS 2413C
Silver Plating, Copper Strike, Low Bake—AMS 2412F
Silver Plating for High Temperature Applications—AMS 2411D
Silver Plating, Electrodeposited, General Requirements for—QQ-S-365D

Tin and Tin Alloys

Electrodeposited Coatings of Tin—ASTM B 545-92
Electrodeposited Coatings of Tin-Lead Alloy (Solder Plate)—ASTM B 579-73
Electrodeposited Coatings of Tin-Nickel Alloy—ASTM B 605-95a
Plating, Tin—AMS 2408F
Plating, Tin-Cadmium (Electrodeposited)—MIL-P-23408B
Plating, Tin-Lead (Electrodeposited)—MIL-P-81728A

Zinc and Zinc Alloys

Electrodeposited Coatings of Zinc on Iron and Steel—ASTM B 633-85
Plating, Zinc-Nickel Alloy—AMS 2417E
Zinc Plating—AMS 2402G

ELECTROLESS AND IMMERSION COATINGS

Nickel

Autocatalytic Nickel-Boron Coatings for Engineering Use—ASTM B 607-91
Autocatalytic Nickel-Phosphorus Coatings on Metals—ASTM B 733
Guide for Autocatalytic (Electroless) Nickel-Phosphorus Deposition on Metals for Engineering Use—ASTM B 656-91
Nickel, Electroless, Plating—AMS 2404C
Nickel Plating, Electroless, Low Phosphorus—AMS 2405B
Nickel-Thallium-Boron or Nickel-Boron Plating, Electroless—AMS 2433A

Tin

Plating, Immersion Tin for Aluminum Alloys—AMS 2409F

Zinc

Aluminum for Solderability, Plating, Zinc Immersion Process—AMS 2420B
Plating Magnesium for Solderability, Zinc Immersion Process—AMS 2421B

MECHANICALLY DEPOSITED COATINGS

Cadmium and Cadmium Alloys

Coatings, Cadmium, Tin-Cadmium, and Zinc (Mechanically Deposited)—MIL-81562B
Coatings of Cadmium-Tin Mechanically Deposited—ASTM B 635-91
Mechanically Deposited Coatings of Cadmium—ASTM B 696-91

Zinc

Coatings, Cadmium, Tin-Cadmium, and Zinc (Mechanically Deposited)—MIL-81562B

HOT-DIP COATINGS

Zinc

Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings—ASTM A 780A
Zinc Coating (Hot-Dip) on Iron and Steel Hardware—ASTM A 153-82R87
Zinc, Locating the Thinnest Spot in a Zinc (Galvanized) Coating on Iron and Steel Articles by the Preece Test—ASTM A 239-89

PHYSICAL VAPOR DEPOSITION COATINGS

Aluminum

Coating, Aluminum, Ion Vapor Deposited—MIL-C-83488C
Coating, Aluminum, Vacuum Deposited—MIL-C-23217B

Cadmium

Coating, Cadmium, Vacuum Deposited—MIL-C-8837B

ANODIC COATINGS

Aluminum and Aluminum Alloys

Anodic Coatings for Aluminum and Aluminum Alloys—MIL-A-8625F
Anodic Oxide Coatings on Aluminum—ASTM B 580-79R89
Anodic Treatment of Aluminum Alloys, Chromic Acid Process—AMS 2470H
Anodic Treatment of Aluminum Alloys, Sulfuric Acid Process, Dyed Coating—AMS 2472C
Anodic Treatment of Aluminum Alloys, Sulfuric Acid Process, Undyed Coating—AMS 2471D
Cleaning and Maintenance of Architectural Anodized Aluminum—AAMA 609.1-85
Hard Coating Treatment of Aluminum and Aluminum Alloys—AMS 2468E
Hard Coating Treatment of Aluminum and Aluminum Alloys, Processing and Performance Requirements—AMS 2469E
Inspection Methods for Clear Anodic Finishes for Architectural Aluminum—AAMA 607.1-77
Measurement of Stain Resistance of Anodic Coatings on Aluminum—ASTM B 136-84
Measuring Thickness of Anodic Coatings on Aluminum with Eddy-Current Instruments—ASTM B 244-79
Specification and Inspection Methods for Electrolytically Deposited Color Anodic Finishes for Architectural Aluminum, Voluntary Guide—AAMA608.1-77
Specification and Inspection Methods for Integral Color Anodic Finishes for Architectural Aluminum, Voluntary Guide—AAMA606.1-76
Standard Test Method for Measurement of Mass of Coating on Anodically Coated Aluminum—ASTM B 137-89

Magnesium Alloys

Electrolytic Treatment for Magnesium Base Alloys, Alkaline Type, Full Coat—AMS 2476B
Magnesium Alloy, Anodic Treatment of—MIL-M-45202C

BLACK OXIDE COATINGS

Blackening Solution for Steel, Touch Up Method—AMS 2484
Coating, Black Oxide—AMS 2485H
Coating, Oxide, Black, for Ferrous Metals—MIL-C-13924C
Finish, Chemical Black, for Copper Alloys—MIL-F-495E
Phosphatizing and Black Oxide Coating of Ferrous Metals—MIL-Hdbk-205A

CHROMATES

Aluminum and Aluminum Alloys

Chemical Conversion Coatings on Aluminum and Aluminum Alloys—MIL-C-5541E
Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys—MIL-C-81706
Chromates on Aluminum—ASTM B 449-93
Preparation of Aluminum and Aluminum Alloy Surfaces for Painting—ASTM D 1730-67R93

Cadmium

Testing Chromate Coatings on Zinc and Cadmium Surfaces—ASTM B 201-80R89

Magnesium Alloys

Magnesium Alloy, Processes for Pretreatment and Prevention of Corrosion on—MIL-M-3171C
Protective Treatments, Magnesium Alloys—AMS 2475E

Zinc

Coatings, Chromate, for Zinc Alloy Castings and Hot-Dip Galvanized Surfaces—MIL-C-17711B
Testing Chromate Coatings on Zinc and Cadmium Surfaces—ASTM B 201-80R89

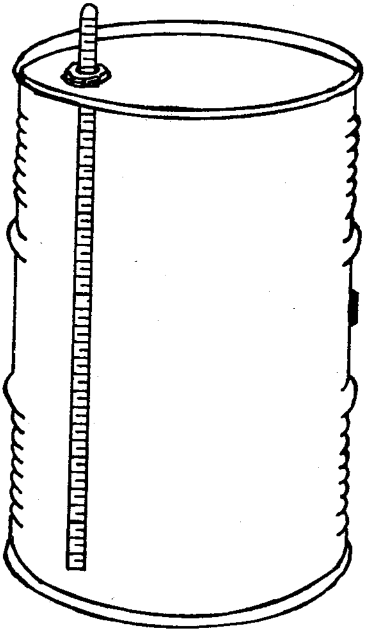
PHOSPHATE COATINGS

Phosphate Coating Compounds, for Phosphating Ferrous Metals—MIL-P-50002B
Phosphate Coatings, Heavy, Manganese or Zinc Base (for Ferrous Metals—DOD-P-16232
Phosphatizing and Black Oxide Coating of Ferrous Metals—MIL-Hdbk-205A

MISCELLANEOUS

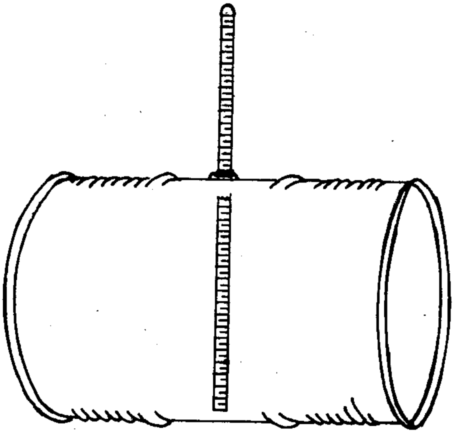
Adhesion of Metallic Coatings—ASTM B 571-91
Copper-Accelerated Acetic Acid Salt Spray (Fog) Testing (CASS Test)—ASTM B 368-85R90
Deoxidizer, Acidic, for Magnesium Alloys—AMS 1538A
Desmutter, Aluminum, Liquid—AMS 1626B
Desmutter, Aluminum, Powdered—AMS 1625B
Liquid Salt Bath Nitriding—AMS 2755C
Measurement of Thickness of Metallic Coatings by the Coulometric Method—ASTM B 504-90
Method for Salt Spray (Fog) Testing—ASTM B 117-90
Microhardness of Electroplated Coatings—ASTM B 578-87R93
Preparation of Aluminum Alloys for Surface Treatments and Inorganic Coatings—MIL-STD-1503B
Surface Treatment (Except Priming and Painting) for Metal and Metal Parts in Aircraft—MIL S-5002D

Inches	Gallons
31	54
30	52
29	50
28	48 1/2
27	47
26	45
25	43 1/2
24	41 1/2
23	40
22	38
21	36 1/2
20	34 1/2
19	33
18	31 1/2
17	29 1/2
16	27 1/2
15	26
14	24 1/2
13	22 1/2
12	21
11	19
10	17 1/2
9	15 1/2
8	14
7	12
6	10 1/2
5	8 1/2
4	7
3	5
2	3 1/2
1	2



Estimating Contents of a Vertical Drum.

Inches	Gallons
20	55
19	52 1/2
18	50
17	47 1/2
16	44 1/2
15	41 1/2
14	38 1/2
13	35
12	32
11	28 1/2
10	25
9	22
8	18 1/2
7	15 1/2
6	12 1/2
5	9 1/2
4	7
3	4 1/2
2	2 1/2
1	0.8



Estimating Contents of a Horizontal Drum.

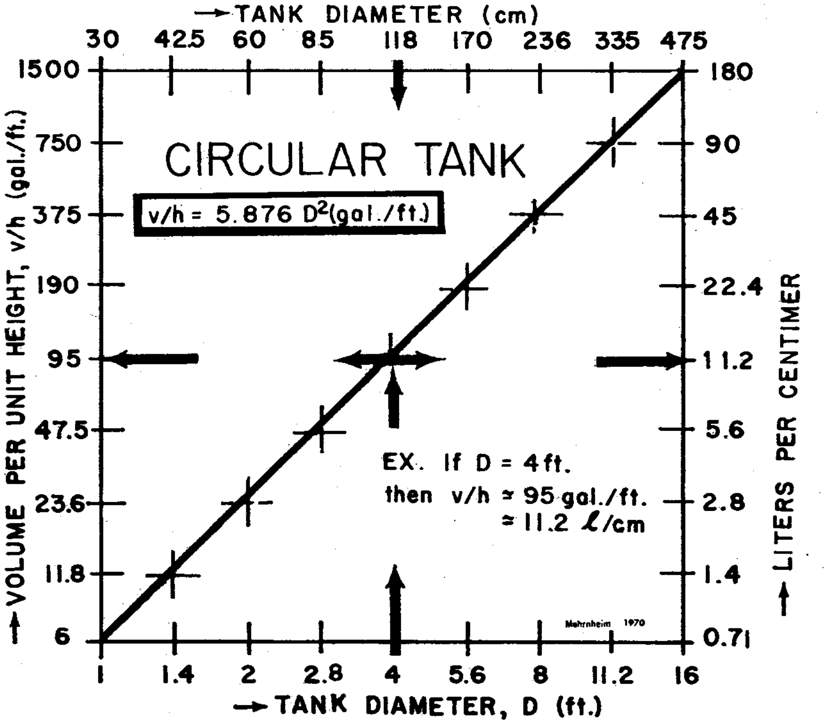
DETERMINING TANK CAPACITY

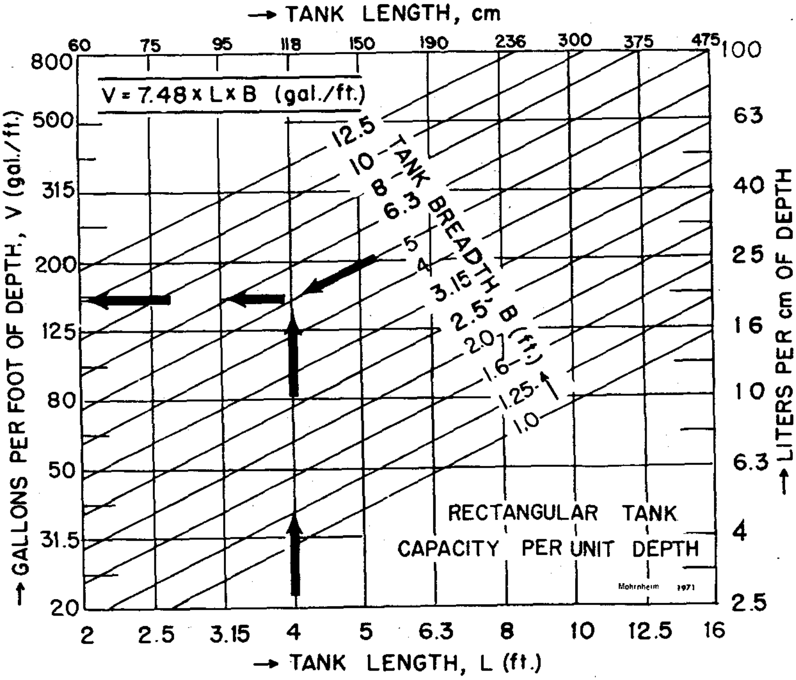
The two graphs shown offer visual guidelines for orientation and quick approximation of the quantity of solution in circular and rectangular containers. The graph "Circular Tank" shows, for round containers, the given diameter in feet at the lower scale. For convenience, the corresponding approximate metric diameter (cm) is shown opposite at the upper scale. Following the direction of the heavy arrows, shown for the Example, D = 4 ft (118 cm), one reads, at the height of the intersection of the corresponding vertical and the diagonal line, the solution volume per unit height (v/h) at the left ordinate, for example 95 gal/ft, corresponding to about 11.2 liters per centimeter shown at the right ordinate.

The graph "Rectangular Tank" shows the given breadth and length of the tank at the lower scale and at the diagonals, for example, B = 5 ft and L = 4 ft. At the intersection of the corresponding vertical and diagonal line, one reads 150 gal/ft at the left ordinate, or about 19 liters per centimeter at the right ordinate.

The solution level (height) is measured either by reading fixed height markings at the inside tank wall or from a ruler dipped to the bottom of the tank. The total solution volume, V (gal), is then equal to the solution height, h (ft), multiplied by V/h (gal/ft).

Note: The *preferred number sequences*, shown on the graphs, represent simplified evenly-divided log scales involving inaccuracies up to about 3 per cent. In most practices this





may be considered as inconsequential. For numerical exact results, the use of the equation at the upper left of the corresponding graph is recommended.

ESTIMATING PLATING TIME

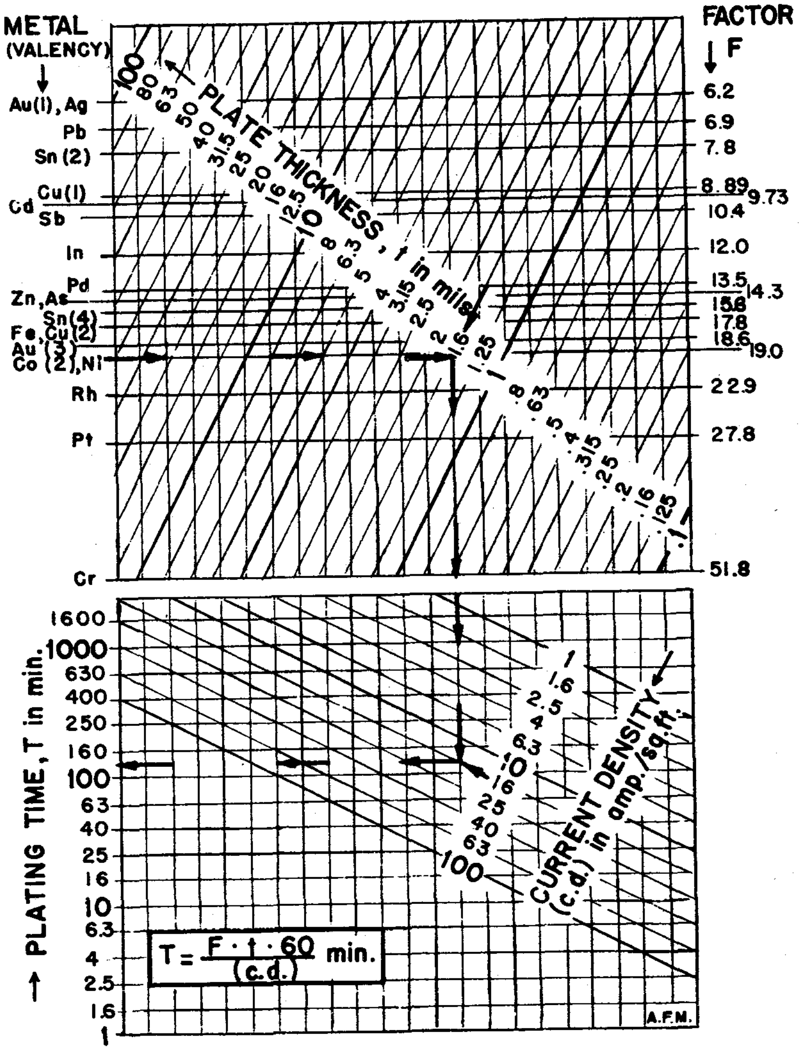
This nomograph is for the practical plater for convenient orientation and approximation of the plating time required to produce a specified plate thickness. The main factors involved are: the kind of metal, its valency in the bath (electrochemical equivalent), density of electroplate, and current density employed.

For using the diagram, one starts from the given plating bath at the upper left ordinate, as illustrated for nickel by the heavy arrows as an example, and goes horizontally to the right to the diagonal indicating the desired plate thickness, for example 1.6 mils. From the point of interception one goes vertically down to the diagonal indicating the applied current density, for example 16 amp./sq. ft. Following the arrow direction to the left, the approximate plating time can then be read from the ordinate, and is for the example somewhat larger than 100 minutes.

In order to obtain numerically exact values, the formula shown in the lower left corner of the diagram should be used. The factor F at the upper right ordinate is equal to the amp.

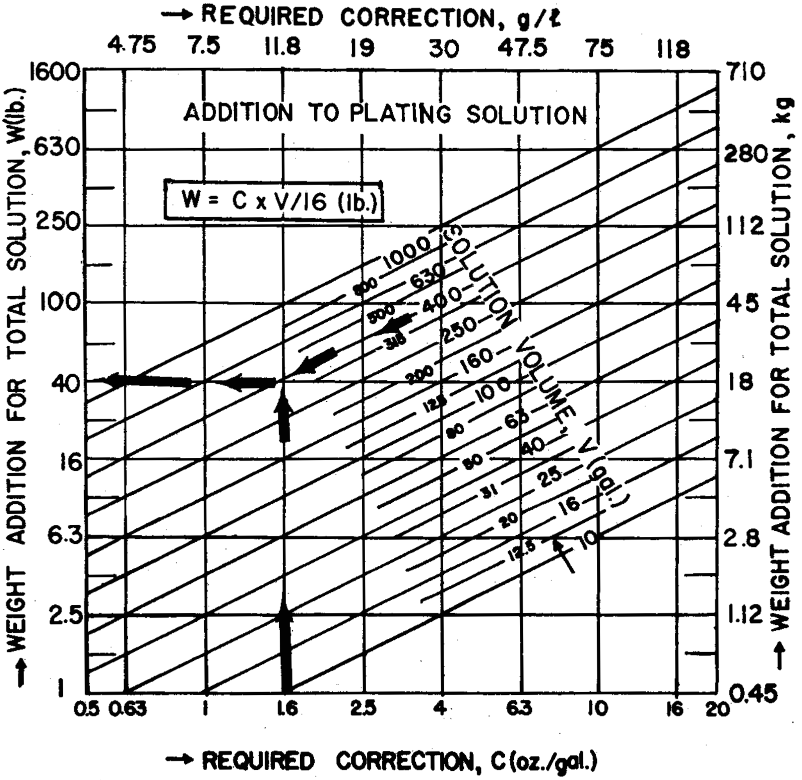
hr./sq. ft. to deposit 0.001 inch of electroplate thickness. The computation using F(Ni) = 19, t = 1.6 mils, c.d. = 16 amp./sq. ft. results in 114 minutes required plating time.

The diagram and the formula are based on 100% cathode efficiency. If the efficiency is less, for example 95% = 0.95, the theoretical plating time must be divided by this value, that is, 114/0.95 = 120 minutes = 2 hours.



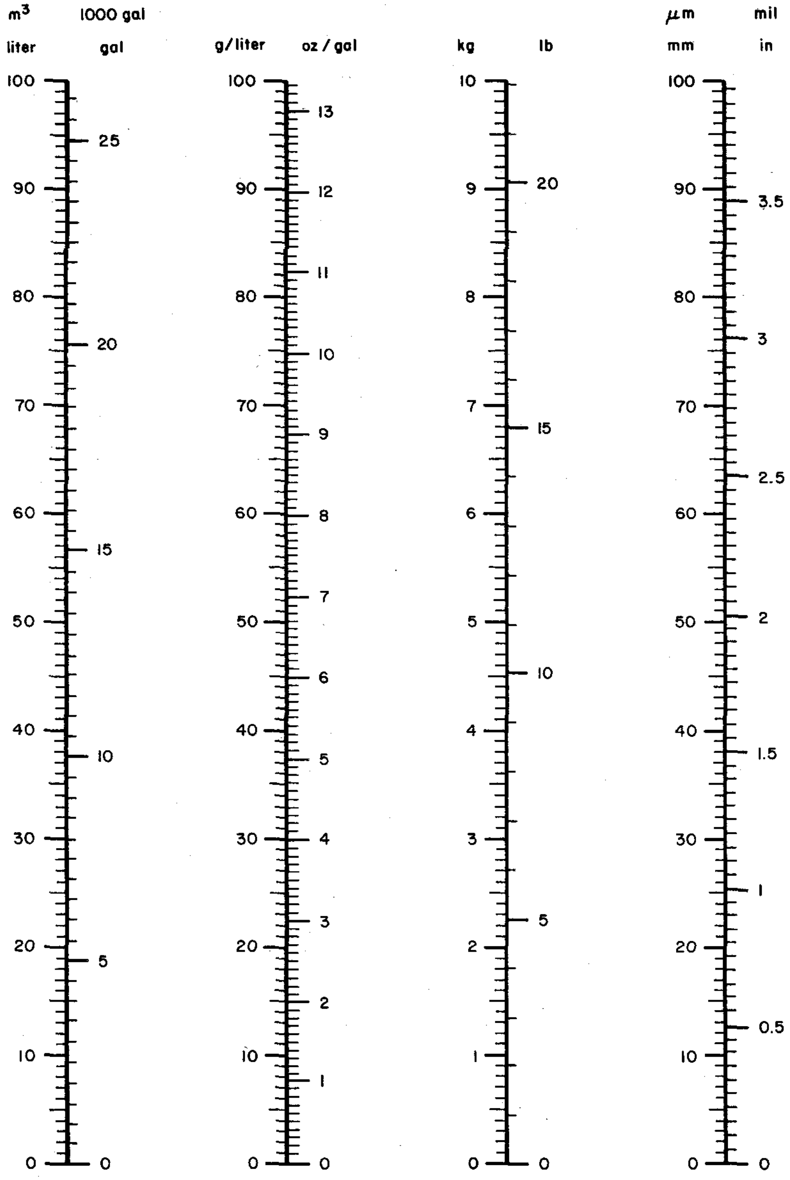
MAKING ADDITIONS TO PLATING SOLUTIONS

The directions of the heavy arrows show the problem solution for the example: if the required addition is 1.6 oz/gal (lower abscissa) for a 400 gal bath (diagonal) then 40 lbs of chemicals must be added (left ordinate). Numerically accurate solutions are obtained by using the inserted equation. For convenience, approximately corresponding metric values are shown at the upper abscissa and right ordinate.

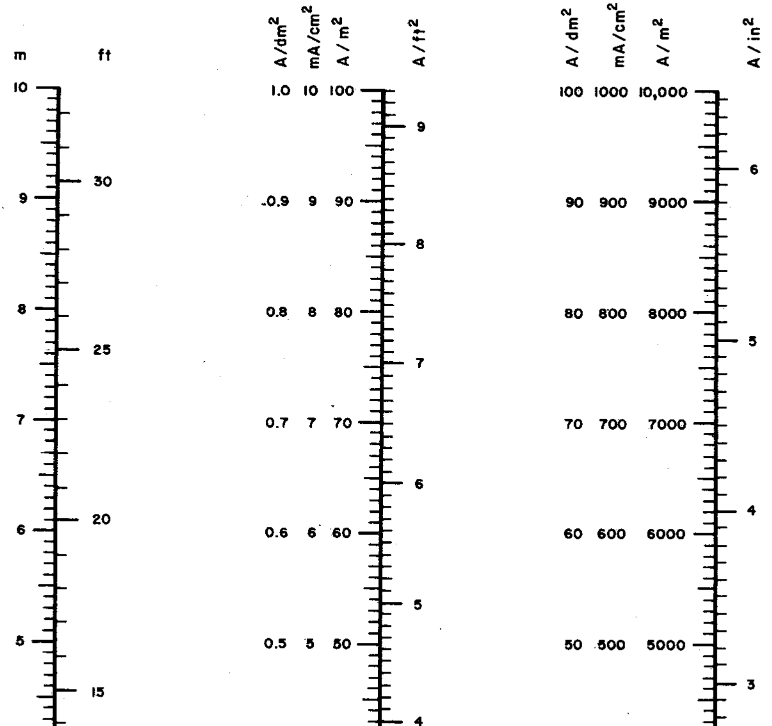


English to Metric Conversion of Units

(Courtesy Fielding Ogburn, Consultant)



English to Metric Conversion of Units
(Courtesy Fielding Ogburn, Consultant)



METAL CONTENTS OF COMMON PLATING SALTS

(Note: Technical products usually vary slightly from stated percentages. Actual metal contents of precious metal salts are usually marked on package.)

Technical Name of Salt	Chemical Formula	Per Cent Metal
Aluminum chloride	$AlCl_3 \cdot 6H_2O$	11.1
Aluminum chloride (anhydrous)	$AlCl_3$	20.3
Aluminum sulfate	$Al_2(SO_4)_3 \cdot 18H_2O$	8.1
Antimony trichloride	$SbCl_3$	53.4
Arsenic trioxide	As_2O_3	75.9
Cadmium chloride	$CdCl_2 2\frac{1}{2}H_2O$	49.3
Cadmium cyanide	$Cd(CN)_2$	68.3
Cadmium oxide	CdO	87.5
Cadmium sulfate	$3CdSO_4 \cdot 8H_2O$	43.3
Chloroplatinic acid	$H_2PtCl_6 \cdot 6H_2O$	37.7
Chromic acid	CrO_3	52.0
Cobalt chloride	$CoCl_2 \cdot 6H_2O$	24.8
Cobalt sulfate	$CoSO_4 \cdot 7H_2O$	21.0
Copper acetate	$Cu(C_2H_3O_2)_2 \cdot H_1O$	31.8
Copper carbonate (basic)	$CuCO_3 \cdot Cu(OH)_2$	57.5
Copper chloride (ic)	$CuCl_2 \cdot 2H_2O$	37.3
Copper cyanide (ous)	$CuCN$	71.0
Copper fluoborate	$Cu(BF_4)_2$	26.8
Copper potassium cyanide	$K_2Cu(CN)_3$	28.9
Copper pyrophosphate	$Cu_2P_2O_7$	42.3
Copper sodium cyanide	$Na_2Cu(CN)_3$	33.9
Copper sulfate	$CuSO_4 \cdot 5H_2O$	25.5
Ferric chloride (anhydrous)	$FeCl_3$	34.5
Ferric chloride	$FeCl_3 \cdot 6H_2O$	20.6
Ferric sulfate (anhydrous)	$Fe_2(SO_4)_3$	27.9
Ferrous ammonium sulfate	$FeSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O$	14.2
Ferrous chloride	$FeCl_2 \cdot 4H_2O$	28.1
Ferrous sulfate	$FeSO_4 \cdot 7H_2O$	20.1
Gold chloride (ic)	$AuCl_3 \cdot 2H_2O$	58.0
Gold cyanide (ous)	$AuCN$	88.3
Gold potassium cyanide	$KAu(CN)_2$	68.3
Gold sodium cyanide	$NaAu(CN)_2$	72.5
Indium chloride	$InCl_3$	51.8
Indium cyanide	$In(CN)_3$	59.4
Indium fluoborate	$In(BF_4)_3$	30.6
Indium sulfate	$IN_2(SO_4)_3$	44.3
Lead carbonate (basic)	$Pb(OH)_2 \cdot 2PbCO_3$	80.1
Lead fluoborate	$Pb(BF_4)_2$	54.4
Nickel acetate	$Ni(C_2H_3O_2)_2 \cdot 4H_2O$	23.6
Nickel ammonium sulfate	$NiSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O$	14.9
Nickel carbonate (basic)	$2NiCO_3 \cdot 3Ni(OH)_2 \cdot 4H_2O$	50.0
Nickel chloride	$NiCl_2 \cdot 6H_2O$	24.7
Nickel cyanide	$Ni(CN)_2 \cdot 4H_2O$	32.1
Nickel fluoborate	$Ni(BF_4)_2$	25.3

(Continued on next page)

Technical Name of Salt	Chemical Formula	Per Cent Metal
Nickel sulfamate	$Ni(NH_2SO_3)_2$	23.4
Nickel sulfate	$NiSO_4 \cdot 6H_2O$	22.3
Palladium chloride	$PdCl_2$	60.0
Palladium diaminodinitrite (P Salt)	$Pd(NH_3)_2(NO_2)_2$	45.8
Platinum chloride (Commercial salt is often chloroplatinic acid)	$PtCl_4 \cdot 5H_2O$	45.7
Platinum diaminodinitrite (P Salt)	$Pt(NH_3)_2(NO_2)_2$	60.8
Potassium stannate	$K_2SnO_3 \cdot 3H_2O$	39.6
Rhodium chloride	$RhCl_3 \cdot 3H_2O$	39.1
Rhodium sulfate	$Rh_2(SO_4)_3$	20.8
Silver chloride	$AgCl$	75.2
Silver cyanide	$AgCN$	80.5
Silver nitrate	$AgNO_3$	63.5
Silver oxide	Ag_2O	93.3
Silver potassium cyanide	$KAg(CN)_2$	54.2
Silver sodium cyanide	$NaAg(CN)_2$	59.0
Silver sulfate	Ag_2SO_4	34.6
Sodium stannate	$Na_2SnO_3 \cdot 3H_2O$	44.5
Sodium tungstate	$Na_2WO_4 \cdot 2H_2O$	55.8
Tin chloride(ous)	$SnCl_2 \cdot 2H_2O$	52.6
Tin fluoborate(ous)	$Sn(BF_4)_2$	40.6
Tin sulfate(ous)	$SnSO_4$	55.3
Tungstic acid	H_2WO_4	73.6
Tungstic oxide	WO_3	79.3
Zinc carbonate	$ZnCO_3$	52.2
Zinc chloride	$ZnCl_2$	48.0
Zinc cyanide	$Zn(CN)_2$	55.7
Zinc fluoborate	$Zn(BF_4)_2$	27.3
Zinc oxide	ZnO	80.3
Zinc pyrophosphate	$Zn_2P_2O_7$	42.9
Zinc sulfate	$ZnSO_4 \cdot 7H_2O$	22.7
Zinc sulfate (anhydrous)	$ZnSO_4$	40.4
Zinc sulfate (exsiccated)	$ZnSO_4 \cdot H_2O$	36.5

CONVERSION FACTORS FOR PLATING CALCULATIONS

Grams per liter (g./L.) multiplied by 0.134 = avoirdupois ounces per gallon (oz./gal.).

Avoirdupois ounces per gallon (oz./gal.) multiplied by 7.5 = grams per liter (g./L.).

Grams per liter (g./L.) multiplied by 0.122 = troy ounces per gallon (tr. oz./gal.).

Troy ounces per gallon (tr. oz./gal.) multiplied by 8.2 = grams per liter (g./L.).

Grams per liter (g./L.) multiplied by 2.44 = pennyweights per gallon (dwt./gal.).

Pennyweights per gallon (dwt./gal.) multiplied by 0.41 = grams per liter (g./L.).

Amperes per square decimeter (amp./dm.^{2}) multiplied by 9.29 = amperes per sq. ft. (amp./ft.^{2}).

Amperes per square foot (amp./ft.^{2}) multiplied by 0.108 = amperes per square decimeter (amp./dm.^{2}).

Fluid ounces per gallon (fl. oz./gal.) multiplied by 7.81 = cubic centimeters per liter (cc./L.).

EQUIVALENTS FOR CONVERTING UNITS OF WEIGHT & MEASURE

Carat (c) (metric)	3.08647 grains; 0.2 gram.
Centimeter (cm.)	0.3937 inch; 0.03281 ft.; 0.01 meter.
Cubic Centimeter (cc.)	0.03381 oz. (fluid); 0.061023 cubic inch; 0.001 liter.
Cubic Foot (ft.^{3} or cu. ft.)	7.481 gallons; 1728 cubic inches; 28.317 liters; 28.317 cubic centimeters.
Cubic Inch (in.^{3} or cu. in.)	0.004329 gallon; 0.5541 ounce (fluid); 16.3872 cubic centimeters.
Foot (ft.)	0.3048 meter; 30.48 centimeters.
Gallon (gal.)	weighs 8.337 lb. at 62°F.; 0.13368 cubic foot; 128 oz. (fluid); 231 cubic inches; 3.7853 liters; 3785.4 cubic centimeters.
Gram (g.)	0.03215 oz. (troy); 0.035274 oz. (avoirdupois); 0.643 pennyweight.
Inch (in.)	2.540 centimeters.
Kilogram (kg.)	2.2046 lb. (avoirdupois); 1000 grams.
Liter (L.)	0.2642 gal.; 0.03532 cu. ft.; 1.0567 quart (liquid); 61.025 cu. in.; 1000 cubic centimeters.
Micrometer (µm)	same as micron.
Micron (µ)	.000039 inch.
Mil	0.001 inch; 0.00254 centimeter; 25.4 microns.
Milligram (mg.)	0.001 gram.
Millimeter (mm.)	0.03937 inch; 0.001 meter; 1000 microns.
Ounce (fluid) (fl. oz.)	0.0078125 gallon; 0.03125 quart (liquid); 1.80469 cubic inches; 29.5737 cubic centimeters.
Ounce (avoirdupois) (oz.)	0.0625 lb. (avoir.); 0.911458 oz. (troy); 18.2292 pennyweights; 437.5 grains; 28.3495 grams.
Ounce (troy)	20 pennyweights; 31.10348 grams.
Pennyweight (dwt.) (troy)	1/20 oz. (troy); 1.552 grams.
Pint (pt.) (liquid)	16 oz. (fluid); 28.875 cu. in.; 473.18 cubic centimeters.
Pound (avoirdupois) (lb.)	1.2153 lb. (troy); 14.583 oz. (troy); 16 oz. (avoir.); 291.667 pennyweights; 7000 grains; 453.592 grams.
Pound (troy) (lb. tr.)	0.82286 lb. (avoir.); 12 oz. (troy); 13.166 oz. (avoir.); 240 pennyweights; 5760 grains; 373.24 grams.
Quart (qt.) (liquid)	0.03342 cubic foot; 0.25 gallon; 32 oz. (fluid); 57.749 cubic inches; 946.358 cubic centimeters.
Square Centimeter (cm.^{2})	0.0010764 sq. ft.; 0.155 sq. in.
Square Decimeter (dm.^{2})	15.50 sq. in.; 0.01 sq. meter; 100 sq. centimeters.
Square Foot	144 sq. in.; 9.29 sq. decimeters.
Square Inch	.007 sq. ft., 6.45 sq. cm.

CENTIGRADE—FAHRENHEIT TEMPERATURE CONVERSION

Look up known temperature in center (bold face type) column. Its equivalent in either F or C can then be found in the appropriate column at left or right.

°F.		°C.	°F.		°C.	°F.		°C.
+ 32.0	**± 0**	−17.78	230.0	**110**	43.33	428.0	**220**	104.44
+ 35.6	**+ 2**	−16.67	233.6	**112**	44.44	431.6	**222**	105.56
+ 39.2	**+ 4**	−15.56	237.2	**114**	45.56	435.2	**224**	106.67
+ 42.8	**+ 6**	−14.44	240.8	**116**	46.67	438.8	**226**	107.78
+ 46.4	**+ 8**	−13.33	244.4	**118**	47.78	442.4	**228**	108.89
+ 50.0	**+10**	−12.22	248.0	**120**	48.89	446.0	**230**	110.00
+ 53.6	**+12**	−11.11	251.6	**122**	50.00	449.6	**232**	111.11
+ 57.2	**+14**	−10.00	255.2	**124**	51.11	453.2	**234**	112.22
+ 60.8	**+16**	− 8.89	258.8	**126**	52.22	456.8	**236**	113.33
+ 64.4	**+18**	− 7.78	262.4	**128**	53.33	460.4	**238**	114.44
+ 68.0	**+20**	− 6.67	266.0	**130**	54.44	464.0	**240**	115.56
+ 71.6	**+22**	− 5.56	269.6	**132**	55.56	467.6	**242**	116.67
+ 75.2	**+24**	− 4.44	273.2	**134**	56.67	471.2	**244**	117.78
+ 78.8	**+26**	− 3.33	276.8	**136**	57.78	474.8	**246**	118.89
+ 82.4	**+28**	− 2.22	280.4	**138**	58.89	478.4	**248**	120.00
+ 86.0	**+30**	− 1.11	284.0	**140**	60.00	482.0	**250**	121.11
+ 89.6	**+32**	± 0.00	287.6	**142**	61.11	485.6	**252**	122.22
+ 93.2	**+34**	+ 1.11	291.2	**144**	62.22	489.2	**254**	123.33
+ 96.8	**+36**	+ 2.22	294.8	**146**	63.33	492.8	**256**	124.44
+100.4	**+38**	+ 3.33	298.4	**148**	64.44	496.4	**258**	125.56
+104.0	**+40**	+ 4.44	302.0	**150**	65.56	500.0	**260**	126.67
107.6	**42**	5.56	305.6	**152**	66.67	503.6	**262**	127.78
111.2	**44**	6.67	309.2	**154**	67.78	507.2	**264**	128.89
114.8	**46**	7.78	312.8	**156**	68.89	510.8	**266**	130.00
118.4	**48**	8.89	316.4	**158**	70.00	514.4	**268**	131.11
122.0	**50**	10.00	320.0	**160**	71.11	518.0	**270**	132.22
125.6	**52**	11.11	323.6	**162**	72.22	521.6	**272**	133.33
129.2	**54**	12.22	327.2	**164**	73.33	525.2	**274**	134.44
132.8	**56**	13.33	330.8	**166**	74.44	528.8	**276**	135.56
136.4	**58**	14.44	334.4	**168**	75.56	532.4	**278**	136.67
140.0	**60**	15.56	338.0	**170**	76.67	536.0	**280**	137.78
143.6	**62**	16.67	341.6	**172**	77.78	539.6	**282**	138.89
147.2	**64**	17.78	345.2	**174**	78.89	543.2	**284**	140.00
150.8	**66**	18.89	348.8	**176**	80.00	546.8	**286**	141.11
154.4	**68**	20.00	352.4	**178**	81.11	550.4	**288**	142.22
158.0	**70**	21.11	356.0	**180**	82.22	554.0	**290**	143.33
161.6	**72**	22.22	359.6	**182**	83.33	557.6	**292**	144.44
165.2	**74**	23.33	363.2	**184**	84.44	561.2	**294**	145.56
168.8	**76**	24.44	366.8	**186**	85.56	564.8	**296**	146.67
172.4	**78**	25.56	370.4	**188**	86.67	568.4	**298**	147.78
176.0	**80**	26.67	374.0	**190**	87.78	572.0	**300**	148.89
179.6	**82**	27.78	377.6	**192**	88.89	590.0	**310**	154.44
183.2	**84**	28.89	381.2	**194**	90.00	608.0	**320**	160.00
186.8	**86**	30.00	384.8	**196**	91.11	626.0	**330**	165.56
190.4	**88**	31.11	388.4	**198**	92.22	644.0	**340**	171.11
194.0	**90**	32.22	392.0	**200**	93.33	662.0	**350**	176.67
197.6	**92**	33.33	395.6	**202**	94.44	680.0	**360**	182.22
201.2	**94**	34.44	399.2	**204**	95.56	698.0	**370**	187.78
204.8	**96**	35.56	402.8	**206**	96.67	716.0	**380**	193.33
208.4	**98**	36.67	406.4	**208**	97.78	734.0	**390**	198.89
212.0	**100**	37.78	410.0	**210**	98.89	752.0	**400**	204.44
215.6	**102**	38.89	413.6	**212**	100.00	770.0	**410**	210.00
219.2	**104**	40.00	417.2	**214**	101.11	788.0	**420**	215.56
222.8	**106**	41.11	420.8	**216**	102.22	806.0	**430**	221.11
226.4	**108**	42.22	424.4	**218**	103.33	824.0	**440**	226.67

ATOMIC WEIGHTS OF THE ELEMENTS

	Symbol	Atomic number	Atomic weight		Symbol	Atomic number	Atomic weight
Aluminum	Al	13	26.97	Molybdenum	Mo	42	95.95
Antimony	Sb	51	121.76	Neodymium	Nd	60	144.27
Argon	A	18	39.944	Neon	Ne	10	20.183
Arsenic	As	33	74.91	Nickel	Ni	28	58.69
Barium	Ba	56	137.36	Nitrogen	N	7	14.008
Beryllium	Be	4	9.02	Osmium	Os	76	190.2
Bismuth	Bi	83	209.00	Oxygen	O	8	16.0000
Boron	B	5	10.82	Palladium	Pd	46	106.7
Bromine	Br	35	79.916	Phosphorus	P	15	30.98
Cadmium	Cd	48	112.41	Platinum	Pt	78	195.23
Calcium	Ca	20	40.08	Potassium	K	19	39.096
Carbon	C	6	12.010	Praseodymium	Pr	59	140.92
Cerium	Ce	58	140.13	Protactinium	Pa	91	231
Cesium	Cs	55	132.91	Radium	Ra	88	226.05
Chlorine	Cl	17	35.457	Radon	Rn	86	222
Chromium	Cr	24	52.01	Rhenium	Re	75	186.31
Cobalt	Co	27	58.94	Rhodium	Rh	45	102.91
Columbium	Cb	41	92.91	Rubidium	Rb	37	85.48
Copper	Cu	29	63.57	Ruthenium	Ru	44	101.7
Dysprosium	Dy	66	162.46	Samarium	Sm	62	150.43
Erbium	Er	68	167.2	Scandium	Sc	21	45.10
Europium	Eu	63	152.0	Selenium	Se	34	78.96
Fluorine	F	9	19.00	Silicon	Si	14	28.06
Gadolinium	Gd	64	156.9	Silver	Ag	47	107.880
Gallium	Ga	31	69.72	Sodium	Na	11	22.997
Germanium	Ge	32	72.60	Strontium	Sr	38	87.63
Gold	Au	79	197.2	Sulfur	S	16	32.066
Hafnium	Hf	72	178.6	Tantalum	Ta	73	180.88
Helium	He	2	4.003	Tellurium	Te	52	127.61
Holmium	Ho	67	164.94	Terbium	Tb	65	159.2
Hydrogen	H	1	1.0080	Thallium	Tl	81	204.39
Indium	In	49	114.76	Thorium	Th	90	232.12
Iodine	I	53	126.92	Thulium	Tm	69	169.4
Iridium	Ir	77	193.1	Tin	Sn	50	118.70
Iron	Fe	26	55.85	Titanium	Ti	22	47.90
Krypton	Kr	36	83.7	Tungsten	W	74	183.92
Lanthanum	La	57	138.92	Uranium	U	92	238.07
Lead	Pb	82	207.21	Vanadium	V	23	50.95
Lithium	Li	3	6.940	Xenon	Xe	54	131.3
Lutecium	Lu	71	174.99	Ytterbium	Yb	70	173.04
Magnesium	Mg	12	24.32	Yttrium	Y	39	88.92
Manganese	Mn	25	54.93	Zinc	Zn	30	65.38
Mercury	Hg	80	200.61	Zirconium	Zr	40	91.22

For most calculations in electroplating the nearest whole numbers may be employed.

ELECTROCHEMICAL EQUIVALENTS

Calculated on Basis of 100% Cathode Efficiency

Metal	*Symbol*	*Valence*	*Atomic Weight (1971)*	*Specific Gravity*	*Weight oz./sq. ft. for 0.001"*	*Thickness in inches of 1 oz./sq. ft.*	*Grams Deposited Per Amp. Hr.*	*Ounces Per Amp. Hr.*	*Amp. Hr. Per. Sq. Ft. to Deposit 0.001"*
Antimony	Sb	3	121.75	6.62	.56	.00180	1.514	.053	10.4
Arsenic	As	3	74.92	5.72	.47	.00213	0.932	.033	14.4
Cadmium	Cd	2	112.40	8.65	.71	.00139	2.097	.074	9.73
Chromium	Cr	6	52.00	7.2	.59	.00169	0.323	.011	51.8
Cobalt (ous)	Co	2	58.93	8.9	.74	.00135	1.099	.039	19.0
Copper (ous)	Cu	1	63.54	8.96	.74	.00134	2.370	.084	8.89
Copper (ic)	Cu	2	63.54	8.96	.74	.00134	1.186	.042	17.8
Gold (ous)	Au	1	197.0	19.3	1.47*	.00068*	7.348	.236*	6.2
Gold (ic)	Au	3	197.0	19.3	1.47*	.00068*	2.449	.079*	18.6
Indium	In	3	114.82	7.31	.56*	.00182*	1.428	.045*	12.0
Iron (ous)	Fe	2	55.85	7.86	.65	.00153	1.042	.037	17.9
Lead	Pb	2	207.19	11.34	.94	.00106	3.865	.136	6.9
Nickel	Ni	2	58.71	8.90	.74	.00135	1.095	.039	19.0
Palladium	Pd	2	106.4	12.0	.86*	.00116*	1.985	.064*	13.5
Platinum	Pt	4	195.09	21.41	1.60*	.00062*	1.819	.058*	27.8
Rhodium	Rh	3	102.91	12.4	.95*	.00106*	1.280	.041*	22.9
Silver	Ag	1	107.87	10.5	.79*	.00126*	4.024	.129*	6.2
Tin (ous)	Sn	2	118.69	7.30	.61	.00164	2.214	.078	7.8
Tin (ic)	Sn	4	118.69	7.30	.61	.00164	1.106	.039	15.6
Zinc	Zn	2	65.38	7.14	.59	.00168	1.219	.043	14.3

*These figures are for 1 troy ounce per square foot.

DIRECTORY

TECHNICAL SOCIETIES AND TRADE ASSOCIATIONS

A

Abrasive Engineering Society P.O. Box 3157 Butler, PA 16003; 724/282-6210

Air and Waste Management Association 1 Gateway Center, 3rd Floor Pittsburgh, PA 15222; 412/232-3444; fax, 412/232-3450

Aluminum Anodizers Council 1000 N. Rand Rd., Ste. 214 Wauconda, IL 60084; 847/526-2010; fax, 847/526-3993

Aluminum Association 900 19th St., N.W., Ste. 300 Washington, DC 20006; 202/862-5100; fax, 202/862-5164

American Architectural Manufacturers Association (AAMA) 1827 Walden Office Square, Ste. 104 Schaumberg, IL 60173; 847/303-5664; fax, 847/303-5774

American Chemical Society (ACS) 1155 16th St., N.W. Washington, DC 20036; 202/872-4600; fax, 202/872-6067

American Conference of Governmental Industrial Hygienists Inc. (ACGIH) 1330 Kemper Meadow Dr., Ste. 600 Cincinnati, OH 45240; 513/742-2020; fax, 513/742-3355

American Electroplaters' and Surface Finishers' Society (AESF) 12644 Research Pkwy. Orlando, FL 32826; 407/281-6441; fax, 407/281-6446

American Galvanizers Association 12200 E. Iliff Ave., Ste. 204 Aurora, CO 80014-1252; 303/750-2900, 800/468-7732; fax, 303/750-2909

American National Standards Institute (ANSI) 11 W. 42nd St., 13th Floor New York, NY 10036; 212/642-4900; fax, 212/398-0023

American Society for Nondestructive Testing (ASNT) 1711 Arlingate Ln., P.O. Box 28518 Columbus, OH 43228-0518; 614/274-6003, 800/222-2768; fax, 614/274-6899

American Society for Quality (ASQ) 611 E. Wisconsin Ave., P.O. Box 3005 Milwaukee, WI 53201-3005; 414/272-8575, 800/248-1946; fax, 414/272-1734

American Society for Testing Materials (ASTM) 100 Barr Harbor Dr. W. Conshohoken, PA 19428-2959; 610/832-9500; fax, 610/832-9555

American Society of Electroplated Plastics (ASEP) 112-J Elden St. Herndon, VA 20170-4809; 703/709-8299; fax, 703/709-1036

American Zinc Association 1112 16th St., N.W., Ste. 240 Washington, DC 20036; 202/835-0164; fax, 202/835-0155

Architectural Spray Coaters Association (ASCA) 895 Doncaster Dr. W. Deptford, NJ 08066; 609/848-6120; fax, 609/251-1243

ASM International 9639 Kinsman Rd. Materials Park, OH 44073-0002; 440/338-5151; fax, 440/338-4634

Association Francaise Des Ingenieurs Et Techniciens De L'Electrolyse Et Des Traitements De Surface 5 rue Le Bua Paris 75020 France; 33 1 40 30 06 80

Australasian Institute of Metal Finishing 21 Bedford St. North Melbourne, Vict. 3051 Australia; 61 3 9326 9633; fax, 61 3 9326 9488

Automotive Bright Products Association 755 W. Big Beaver, Ste. 1100 Troy, MI 48084; 248/362-4200; fax, 248/362-3428

B

British Surface Treatment Suppliers Assn. Federation House, 10 Vyse St. Birmingham B18 6LT U.K.; 44 121 237 1123; fax, 44 121 237 1124

C

Canadian Association of Metal Finishers 68 Burnhamthorpe Crescent Etobicoke, Ont. M9A 1G7 Canada; 416/237-1400 fax, 416/237-1400

Chemical Coaters Association Int'l. (CCAI) P.O. Box 54316 Cincinnati, OH 45254; 513/624-6767; fax, 513/624-0601

Copper Development Association Inc. 260 Madison Ave. New York, NY 10016; 212/251-7200; fax, 212/251-7234

D

Deutsche Gesellschaft fur Galvano und, Oberflachentechnik e.V. (DGO) Horionplatz 6 Dusseldorf D-40213 Germany; 49 211 132 381; fax, 49 211 327 199

E

Electrochemical Society (ECS) 10 S. Main St. Pennington, NJ 08534-2896; 609/737-1902; fax, 609/737-2743

European General Galvanizers Association (EGGA) Croudace House, Godstone Road Caterham, Surrey CR3 6RE England; 44 183 331 277; fax, 44 183 331 287

F

Federation of Societies for Coatings Technology (FSCT) 492 Norristown Rd. Blue Bell, PA 19422; 610/940-0777; fax, 610/940-0292

G

Gas Research Institute 8600 W. Bryn Mawr Ave. Chicago, IL 60631; 773/399-8100; fax, 773/399-8170

Gold Institute 1112 16th St., N.W., Ste. 240 Washington, DC 20036; 202/835-0185; fax, 202/835-0155

H

Halogenated Solvents Ind. Alliance Inc., (HSIA) 2001 L St., N.W., Ste. 506A Washington, DC 20036; 202/775-0232; 888/594-4742 fax, 202/833-0381

Hydraulic Institute 9 Sylvan Way Parsippany, NJ 07054-3802; 973/267-9700; fax, 973/267-9055

I

Industrial Heating Equipment Association 1111 N. 19th St., Ste. 425 Arlington, VA 22209; 703/525-2513; fax, 703/525-2515

Institute of Metal Finishing (IMF) Exeter House, 48 Holloway Rd. Birmingham B1 1NQ England; 44 121 622 7387; fax, 44 121 666 6316

International Cadmium Association P.O. Box 924 Great Falls, VA 22066; 703/759-7400; fax, 703/759-7003

International Copper Association Ltd. 260 Madison Ave. New York, NY 10016; 212/251-7240; fax, 212/251-7245

International Hard Anodizing Assoc. P.O. Box 579 Moorestown, NJ 08057; 609/234-0330; fax, 609/727-9504

International Lead Zinc Research Organization Inc. (ILZRO) 2525 Meridian Pkwy., P.O. Box 12036 Research Triangle Pk., NC 27709-2036; 919/361-4647; fax, 919/361-1957

International Magnesium Association 1303 Vincent Pl., Ste. One McLean, VA 22101; 703/442-8888; fax, 703/821-1824

International Precious Metals Institute (IPMI) 4400 Bayou Blvd., Ste. 18 Pensacola, FL 32503; 850/476-1156; fax, 850/476-1548

International Thermal Spray Association 9639 Kinsman Rd. Materials Park, OH 44073-0002; 440/338-1950; fax, 440/338-4634

International Titanium Association 1871 Folsom St., Ste. 200 Boulder, CO 80302; 303/443-7515; fax, 303/443-4406

IPC, Association Connecting Electronics Ind. 2215 Sanders Rd., Ste. 250 South Building Northbrook, IL 60062-6135; 847/509-9700; fax, 847/509-9798

ITRI Ltd. Kingston Ln., Uxbridge Middlesex UB8 3PJ U.K.; 44 018 527 2406; fax, 44 018 525 1841

L

Lead Industries Association Inc. 13 Main St. Sparta, NJ 07871; 973/726-5323; fax, 973/726-4484

M

Manufacturing Jewelers & Suppliers of America One State St., 6th Fl. Providence, RI 02908-5035; 401/274-3840; fax, 401/274-0265

Metal Finishers' Assoc. of India 4, Satguru Industrial Estate, Vishweshwar Nager Rd., Off Aarey Rd. Goregaon (E), Mumbai 400 063 India; 91 028 741 072; fax, 91 028 747 301

Metal Finishing Association Federation House, 10 Vyse St. Birmingham B18 6LT U.K.; 44 121 237 1123; fax, 121 237 1124

Metal Finishing Suppliers' Association (MFSA) 112-J Elden St. Herndon, VA 20170-4809; 703/709-5729; fax, 703/709-1036

N

NACE International 1440 S. Creek Dr. Houston, TX 77084-4906; 281/228-6200; fax, 281/228-6300

National Association of Architectural Metal Manufacturers (NAAMM) 8 S. Michigan Ave., Ste. 1000 Chicago, IL 60603; 312/332-0405; fax, 312/332-0706

National Association of Metal Finishers (NAMF) 112-J Elden St. Herndon, VA 20170-4809; 703/709-8299; fax, 703/709-1036

National Coil Coaters Association (NCCA) 401 N. Michigan Ave., Ste. 2200 Chicago, IL 60611; 312/644-6610; fax, 312/321-6869

National Electrical Manufacturers Association (NEMA) 1300 N. 17th St., Ste. 1847 Rosslyn, VA 22209; 703/841-3200; fax, 703/841-3300

National Fire Protection Association (NFPA) 1 Batterymarch Pk., P.O. Box 9101 Quincy, MA 02269-9101; 617/770-3000, 800/344-3555; fax, 617/770-0700

National Paint & Coatings Association (NPCA) 1500 Rhode Island Ave., N.W. Washington, DC 20005; 202/462-6272; fax, 202/462-8549

Nickel Development Institute (NiDi) 214 King St., W., Ste. 510 Toronto, Ont. M5H 3S6 Canada; 416/591-7999; fax, 416/591-7987

O

Oil & Colour Chemists' Association Priory House, 967 Harrow Rd. Wembley, Middlesex HA0 2SF England; 44 181 908 1086; fax, 44 181 908 1219

P

Paint & Powder Finishing Association Federation House, 10 Vyse St. Birmingham B18 6LT U.K.; 44 121 237 1123; fax, 44 121 237 1124

Porcelain Enamel Institute 4004 Hillsboro Pike, Ste. 224B Nashville, TN 37215; 615/385-5357; fax, 615/385-5463

Powder Coating Institute (PCI) 2121 Eisenhower Ave., Ste. 401 Alexandria, VA 22314; 703/684-1770, 800/988-2628; fax, 703/684-1771

R

Radtech International North America 60 Revere Dr., Ste. 500 Northbrook, IL 60062; 847/480-9576; fax, 847/480-9282

Robotic Industries Association 900 Victors Way, P.O. Box 3724 Ann Arbor, MI 48106; 734/994-6088; fax, 734/994-3338

S

Silver Institute 1112 116th St., N.W., Suite 240 Washington, DC 20036; 202/835-0185; fax, 202/835-0155

Society for the Advancement of Material and Process Engineering (SAMPE) 1161 Parkview Dr. Covina, CA 91724-3748; 626/331-0616, 800/562-7360; fax, 626/332-8929

Society of Automotive Engineers (SAE) 400 Commonwealth Dr. Warrendale, PA 15096-0001; 724/772-7129, 800/832-6723; fax, 724/776-1615

Society of Manufacturing Engineers (SME) One SME Dr., P.O. Box 930 Dearborn, MI 48121-0930; 313/271-1500, 800/733-4763; fax, 313/271-2861

Society of Plastics Engineers Inc. (SPE) 14 Fairfield Dr., P.O. Box 403 Brookfield, CT 06804-0403; 203/775-0471; fax, 203/775-8490

Society of Vacuum Coaters (SVC) 71 Pinon Hill Pl., NE Albuquerque, NM 87122-1914; 505/856-7188; fax, 505/856-6716

SSPC: The Society for Protective Coatings 40 -24th St., 6th Floor Pittsburgh, PA 15222-4656; 412/281-2331, 800/837-8303; fax, 412/281-9992

Surface Engineering Association Federation House, 10 Vyse St. Birmingham B18 6LT U.K.; 44 121 237 1122; fax, 44 121 237 1124

U

Unified Abrasives Manufacturers' Association 30200 Detroit Rd. Cleveland, OH 44145-1967; 440/899-0010; fax, 440/892-1404

W

Water Environment Federation 601 Wythe St. Alexandria, VA 22314-1994; 703/684-2400, 800/666-0206; fax, 703/684-2407

COURSES IN METAL FINISHING

Types of courses offered are indicated in capital boldface letters, as **C** *for correspondence courses or home study;* **S** *for seminars;* **P** *for part-time courses; and* **F** *for full time classes. For current information on courses offered, tuition, fees, starting dates, and duration of classes, please contact the institution, company, or individual offering the class.*

American Electroplaters' and Surface Finishers' Society (**C, S**), 12644 Research Pkwy., Orlando, FL 32826; 407/281-6441; fax, 407/281-6446

California State University, Sacramento (**C**), Office of Water Programs, 6000 J St., Sacramento, CA 95819-6025; 916/278-6142; fax, 916/278-5959

Garden State Branch of the AESF (**P**), c/o Tilton Rack & Basket Corp., 66 Passaic Ave., Fairfield, NJ 07004; 201/226-6010

(Hard) Chromium Consultants School (**C**), P.O. Box 44082, Cleveland, OH 44144; 216/631-9090; fax, 216/631-9060

Institute of Metal Finishing (**C, S**), Exeter House, 48 Holloway Rd., Birmingham B1 1NQ, England; 0121/622-7387; fax, 0121/666-6316

Kushner Electroplating School, Joseph B. (**C, S**), 732 Glencoe Ct., Sunnyvale, CA 94087; 408/749-8652; fax, 408/749-0176

Los Angeles Branch of the AESF (**P**), c/o Specialized Consulting, 1667 Las Virgenes Canyon Rd. #2, Calabasas, CA 91302; 818/880-4271

Metals Engineering Institute Education Department (**C, S**), 9639 Kinsman Rd., Materials Park, OH 44073; 216/338-5151; fax, 216/338-4634

New York Branch of AESF (**P**), c/o Zierick Mfg., Mt. Kisco, NY 10549; 914/666-2911, ext. 240; fax, 914/666-0216

Weiner, Milton (**P**), 28121 Ridgethorne Ct., Rancho Palos Verdes, CA 90275-3253; 310/544-0470

TRADE NAMES

All trade names consisting of numbers or letters not spelling out a pronounceable word are not included. In addition, trade names exactly the same as the firm name or the same as the common abbreviation for the firm name are not included.

A

ABCO—Steel burnishing balls and shapes. Abbott Ball Co.
ABCUT—Steel media for vibratory mass finishing. Abbott Ball Co.
ABRASER—Surface-coating test equipment. Taber Industries
ABRASOTEX—Nylon-padded abrasive finishing wheel. Merit Abrasive Products Inc.
ABSOL—Cleaning solvents. Detrex Corp., Solvents and Environmental Services Div.
ABZOL—Solvent cleaners. Albemarle Corp.
ACCELEREX—High-speed gold process. Enthone-OMI Inc.
ACCLAIM—Addition agent for acid-copper plating. Taskem Inc.
ACCOMET—Pretreatment process. Albright & Wilson Americas
ACCU-SYSTEMS—On-line analytical process control system. PPG Pretreatment & Specialty Products
ACCU-THERM—Plate-type heat exchanger. Paul Mueller Co.
ACCUASSAY—Metal salts. Engelhard Electro Metallics Div.
ACCUBRADE—Aluminum oxide abrasive blend for deburring. S.S. White Technologies Inc.
ACCUDERM—Nondestructive coating and plating thickness gauge. Veeco Industrial Measurement
ACCUGUARD—Module for automatic cleaning and calibration of pH electrodes. Leeds & Northrup, A Unit of General Signal
ACCUPEEN—Glass bead blend for surface finishing. S.S. White Technologies Inc.
ACHROLYTE—A tin-cobalt alloy plating process. Enthone-OMI Inc.
ACIDEX—Dry acid activating salts. Atotech USA Inc.
ACIDTEX—Acid salt compounds. Starlite Technical Service Inc.
ACIDTROL—Activators, additives for surface pretreatments. Pax Surface Chemicals Inc.
ACRI-LEA—Treatment for cotton and sisal buffs. JacksonLea, A Unit of Jason Inc.
ACRYL-AC—Dipping clear lacquer. Pavco Inc.
ACRYLIFT—Paint stripper. DuBois, Div. of Diversey Lever
ACTANE—Acid pickling additive. Enthone-OMI Inc.
ACTIDIP—Surface preparation agent. Elf Atochem North America Inc.
ACTIM&T—Dry acid salts and additives. Atotech USA Inc.
ACTISALT—Granular acid salts. McGean-Rohco Inc.
ACTIUM—Alkaline electrolytical activator for nickel. Advanced Chemical Co.
ACTIV-8—Pickling acid accelerator. MacDermid Inc.
ACTIVATE—Additive for paint stripping and cleaning. DuBois, Div. of Diversey Lever
ACTONALL—Dry acid pickling salts. Plating Resources Inc.
ACTREL—Degreasing solvents. Exxon Chemical Co.
ACTS—Automatic control touch-screen systems. HBS Equipment Corp.
ACTUSOL—Emulsifying solvent for removing soils. DuBois, Div. of Diversey Lever
ADDIPOSIT—Processes for plating on plastics. Shipley Ronal
ADDPLATE—Electroless nickel additive. Surface Technology Inc.
ADHERE—Pretreatment materials for plastics. BetzDearborn, Div. of Hercules Inc.
ADHERITE—Conversion coating and cleaner. MacDermid Inc.
ADJUST-A-VIBE—Vibratory motion control for mass finishing. Sweco Inc.
ADMIRAL—Submersible pump and filter system. SERFILCO Ltd.
ADVANCE—Gas chlorinators. Capital Controls Co. Inc.
ADVANTAGE—High-speed wire plating system. Carolinch Co.
AEROBELL—Rotary spray atomizer. ITW Ransburg Electrostatic Systems
AERONIKL—Nickel sulfamate selective plating solution. Sifco Selective Plating, Div. of Sifco Industries Inc.
AIRBRASIVE—Abrasive jet machining and finishing equipment. S.S. White Technologies Inc.
AIRHEAD—Tank ventilation system. Conserve Engineering Co. LLC
AIRSCRUBBER—Scrubbing system for atmospheric evaporator. Poly Products Corp.
AIRWALL—Dust control equipment for dry stripping systems. Envirosystems Equipment Co. Inc.
AIRWAY—Ventilated buffing wheel. JacksonLea, A Unit of Jason Inc.
AJA-KLEEN—Parts washers. Ramco Equipment Corp.
AJA-LIF—Parts washer with agitation. PPG Pretreatment & Specialty Products
AL BRITE—Aluminum bright dip. Heatbath Corp.
ALADDIN—Anodizing clamp. Sequel Corp.
ALBOND—Chromate conversion coating for aluminum. Brent America Inc.
ALBONE—Hydrogen peroxide. DuPont Co.
ALBRIFIN—Clear acrylic resin coating dyed prior to curing. Albright & Wilson Americas
ALBRISTAR—Bright nickel plating process. Albright & Wilson Americas
ALCHROGOLD—Yellow chromate conversion coating for aluminum. American Chemical & Equipment
ALCHROME—Chromate conversion coating for aluminum. Heatbath Corp.
ALCLEAN—Alkaline cleaner for aluminum. Oakite Products Inc., A Member of The Chemetall Group
ALCOJET—Ultrasonic cleaner. Alconox Inc.
ALCOR—Nickel-based sealing compound for anodized aluminum. Iso-Cor Inc.
ALCROMAX—A chemical conversion coating process for aluminum and its alloys. Pax Surface Chemicals Inc.
ALDACS—Metal cleaners. Aldoa Co.
ALDO-KOTES—Conversion coating processes. Aldoa Co.
ALDOLYTES—Metal cleaners. Aldoa Co.
ALDOX—Aluminum deoxidizer. Elf Atochem North America Inc.
ALECRA—Chromium plating processes. Albright & Wilson Americas
ALEXIS—Satin finish chemical treatment for aluminum and sealant. Albright & Wilson Americas
ALGASORB—Ion exchange resin. Bio-Recovery Systems Inc.
ALGOCLAD—Gold plating process. Enthone-OMI Inc.
ALK-CU-STRIP—Recyclable stripper for copper. Phibro-Tech Inc., Environmental Recovery Services Div.
ALKA-STAR—Alkaline zinc plating process. Atotech USA Inc.
ALKALOX—Soak cleaner. McGean-Rohco Inc.
ALKALUME—Metal cleaners for aluminum and magnesium. McGean-Rohco Inc.
ALKALYTE—Metal cleaners. Starlite Technical Service Inc.
ALKAMAX—Alkaline zinc noncyanide plating processes. Chemtech Finishing Systems Inc.
ALKAWAY—Alkaline cleaners. Chemtech Finishing Systems Inc.
ALKLEAN—Aluminum cleaners for electroless nickel processes. Atotech USA Inc.
ALKMAX—Noncyanide alkaline zinc plating process. American Chemical & Equipment
ALL STRIKE—Alkaline electroless nickel strike. MacDermid Inc.
ALMAC—Mechanically deposited zinc-aluminum. MacDermid Inc.
ALMECOLOR—Electrolytic color system for aluminum. Henkel Surface Technologies
ALODINE—Protective coating chemical for aluminum. Henkel Surface Technologies
ALPHA—Electroless nickel plating process. Atotech USA Inc.
ALPHOS—Phosphate coating process. Alchem Corp.

ALPREP—Plating pretreatment process for aluminum. MacDermid Inc.
ALSATIN—Aluminum etching chemical. Okuno Chemical Industries Co. Ltd.
ALSCOR—Plating barrel equipment, accessories, plating plants, and corrosion test cabinets. Singleton Corp.
ALSTAN—Process for preparing aluminum for plating; also for immersion tin plating of aluminum. Atotech USA Inc.
ALTIX—Bright silver bath. Dr. Ing. Max Schlotter
ALTRASEAL—Water-based and high solids coatings. Chemtech Finishing Systems Inc.
ALU-FILM—Chromium-free conversion coating for aluminum. JacksonLea, A Unit of Jason Inc.
ALU-KLEEN—Etching noncaustic alkaline cleaners. Heatbath Corp.
ALUM ETCH—Aluminum etching agent. Heatbath Corp.
ALUM-KLEEN—Alkaline cleaner for aluminum. Deveco Corp.
ALUM-SEAL—Anodizing sealants. Plating Resources Inc.
ALUM-SURF-PREP—Room temperature surface treatment for aluminum. Arcal Chemicals Inc.
ALUM-TREAT—Zincate and surface treatments for aluminum. Plating Resources Inc.
ALUMA BLACK—Room temperature blackening process for aluminum. Birchwood Laboratories Inc.
ALUMA ETCH—Aluminum etchants. A Brite Co.
ALUMA-BRITE—Bright dip for aluminum. Heatbath Corp.
ALUMASOL—Aluminum soak cleaner. Haviland Products Co.
ALUMETCH—Desmuts for preparing aluminum for plating. Atotech USA Inc.
ALUMIBOND—Conversion coating for aluminum. ACI Chemicals Inc.
ALUMON—Zincate process for plating on aluminum. Enthone-OMI Inc.
ALUMSEAL—Zincate process for plating on aluminum. Atotech USA Inc.
ALUNDUM—Aluminum oxide abrasives for polishing and tumbling. Norton Co.
ALUSEAL—Antismutting agent for anodize sealers. Clariant Corp.
AMATEX—Buffs. Matchless Metal Polish Co.
AMBER—Heavy duty buff. Schaffner Mfg. Co. Inc.
AMBICID—Detergent additive for acid pickle baths. Metalline Corp.
AMBIENOL—Pickling bath inhibitor with surfactant. Metalline Corp.
AMER-GLAS—Disposable air filter. Snyder General Corp. American Air Filter
AMERIBRIGHT—A series of noncyanide zinc brighteners. Pavco Inc.
AMERIZINC—Zinc chloride plating system. Pavco Inc.
AMIBRITE—Bright dip for stainless steel. Sur-Fin Chemical Corp.
AMPHIB—Solution filter system. Sethco Div., Met-Pro Corp.
AMPREP—Metal recovery equipment. AmeriChem Engineering Services
AMTIN—Matte tin plating process. AmeriChem Engineering Services
ANAQIK—Reagents and methods for analyses of plating and other processes. Pax Surface Chemicals Inc.
ANDERFLEX—Abrasive wheels. Anderson Products Inc. Sub. of Wilton Corp.
ANO-PUR—Ion exchange system for anodizing. Eco-Tec Inc.
ANODAL—Low temperature anodizing sealant. Clariant Corp.
ANODEX—Reverse current steel cleaner. MacDermid Inc.
ANODICOTE—Anodic electrocoating system. George Koch Sons LLC
ANOGATOR—Anodizing clamp. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
ANOKLEEN—Lead anode cleaning compound. Atotech USA Inc.
APPLIKON—On-line monitoring instrument. Brinkmann Instruments Inc.
AQUA-EASE—Aqueous cleaners. Hubbard-Hall Inc.
AQUA-LOK—Automatic water shut-off valve. Southwest United Industries Inc.
AQUA-PORE—Filtration membranes. Ionics Inc., Separations Technology Div.
AQUA-SHED—Rinse aids for metal and plastic parts. BetzDearborn, Div. of Hercules Inc.
AQUABLOCK—Electrostatic voltage blocking system. ITW Ransburg Electrostatic Systems
AQUACLEEN—Solvent-free, nonchelated, nonsilicated biodegradable cleaner. Hubbard-Hall Inc.
AQUAFAST—Aqueous cleaning machine. FPI Systems Inc.
AQUALAC—Water-based lacquer. MacDermid Inc.
AQUAMAG—Magnesium hydroxide powder for waste neutralization. Premier Services Corp.
AQUAMASTER—Parts cleaning systems. Alliance Mfg. Inc.
AQUAMATE—Fluid recycling system. Sanborn Technologies, A Waterlink Co.
AQUAMATE—Parts cleaning systems. Alliance Mfg. Inc.
AQUANOX—Sprayable alcohol solvents. Kyzen Corp.
AQUAPHOS—Organic coatings used over zinc phosphate. Texo Corp.
AQUAPOLISH—Chemical polish for copper and copper alloys. Metalline Corp.
AQUAPURE—Wastewater treatment compounds. Hubbard-Hall Inc.
AQUARATOR—Flow restrictor jet pump for rinse water agitation. Aqualogic Inc.
AQUARIUS—Ultrasonic cleaning system. CAE Ultrasonics
AQUASOLVE—Terpene-based cleaners and degreasers. Atotech USA Inc.
AQUASWITCH—Computer-controlled rinse water switch. Myron L Co.
AQUATENE—Alkaline cleaners. Graymills Corp.
AQUATION—Chemicals for water treatment. Aldoa Co.
AQUATREX—Aqueous ultrasonic cleaning system. L&R Mfg. Co.
AQUATROL—Rinse water additive. Pax Surface Chemicals Inc.
AQUAVAP—Vapor compression unit. Licon Inc.
AQUAVERT—Aqueous cleaner. Detrex Corp., Solvents and Environmental Services Div.
ARC BAR—Power supply for electrostatic spraying. ITW Ransburg Electrostatic Systems
ARGENTO BRUSH—Silver brush plating gel. Technic Inc.
ARGENTOMERSE—Bright immersion silver process. Technic Inc.
ARIES—Computer-controlled hoist/transporter. Mesa West Inc.
ARMAKLEEN—Aqueous cleaners. Church & Dwight Co. Inc.
ARMEX—Sodium carbonate based blasting media. Church & Dwight Co. Inc.
ARMOR-CLAD—Universal uncoated plating rack. Mitchell-Bate Co.
ARMOR—Electroless nickel plating processes. McGean-Rohco Inc.
ARRESTALL—Self-contained dust collector. Snyder General Corp. American Air Filter
ARROWBLAST—Pressure blasting abrasive. Norton Co.
ARTAB—Greaseless compound for satin finishing. JacksonLea, A Unit of Jason Inc.
ARTFORM—Gold electroforming system for 14 and 18 karat gold. Enthone-OMI Inc.
ASPLIT—Acid-resisting cement. Elf Atochem North America Inc.
ASSET—Surface measuring pulse power supply. AmeriChem Engineering Services
ASTRO—A prefix for cadmium, nickel, and zinc plating bath additives. Bison Corp.
ATLANTIC—Greaseless buffing compound for satin finishing. JacksonLea, A Unit of Jason Inc.
ATOMEX—Immersion gold plating water-soluble salts. Engelhard Electro Metallics Div.
AUBEL—Autocatalytic soft gold plating process. Uyemura International Corp.
AURABRITE—Acid gold plating processes. Engelhard Electro Metallics Div.
AURALL—Gold plating process. Shipley Ronal
AURASTAN—Tin and tin-lead plating processes. Pax Surface Chemicals Inc.
AURIC—Gold plating baths and equipment. OMG Fidelity
AURICAL—Immersion gold plating process. Uyemura International Corp.
AURION-X—Gold recovery system. Enthone-OMI Inc.
AURIQUICK—Gold plating process. Dr. Hesse & Cie.
AURO SPOT—High-speed gold plating process. Shipley Ronal
AURO-YELLO—Imitation gold. Auromet Corp.
AUROBOND—Gold strike solution. Enthone-OMI Inc.
AUROTECH—Tab plating machine. Technic Inc., Equipment Div.
AUROWHITE—Imitation rhodium. Auromet Corp.
AURUNA—Gold plating process. Degussa Hüls Corp.
AUTO-VAC—Rotary drum precoat vacuum filter. Alar Engineering Corp.

AUTOBETA—Thickness tester. Asoma-TCI
AUTOBOND—Pretreatment processes for surface preparation. Stapleton Technologies
AUTOBRADER—Orbital mass-finishing machine. USFilter/VL Rampe
AUTOCOATER—Automatic electrostatic powder coating machine. ITW Gema
AUTOGRAVITY—Automatic gravity filter system. SERFILCO Ltd.
AUTOJET—Automatic spray gun for airless paint spraying. Spraying Systems Co.
AUTOLOAD—Ultrasonic vapor degreaser. CAE Ultrasonics
AUTONIC—Electroless nickel coatings. Stapleton Technologies
AUTOPHORETIC—Process for depositing paint onto metal surfaces. Henkel Surface Technologies
AUTOTEST—Thickness tester. Asoma-TCI
AUTRONEX—Acid gold plating process. Enthone-OMI Inc.
AUTRONIC—Gold recovery equipment. RRC Agmet Inc.
AXAREL—Cleaning solvents. Detrex Corp., Solvents and Environmental Services Div.
AXAREL—Hydrocarbon-based cleaning agents. Petroferm Inc.
AZTECH—Acid zinc plating process. Atotech USA Inc.

B

B-GON—Mist eliminator. Kimre Inc.
BALLOTINI—Glass spheres for blast cleaning, stress relief, etc. Potters Industries Inc., An Affiliate of the PQ Corp.
BARR-O-CELL—Test equipment for barrel plating procedures. Larry King Corp.
BARRACUDA—Chemical solution feeder. Pulsafeeder Inc., A Unit of Idex Corp.
BARREL SURF—Steel soak cleaner. Haviland Products Co.
BARREL-AIRE—Connector system for air-driven plating barrel rotation. Mid-Western Processes Inc.
BARRETT—Sulfamate nickel plating process. MacDermid Inc.
BATCH MASTER—Waste treatment system. Wastewater Treatment Systems
BATH MINDER—Chemical feeder. Systematics Inc.
BEAR-TEX—Surface blending nonwoven abrasive belts and disks. Norton Co.
BEAR—Abrasive belts and pressure-sensitive masking tapes. Norton Co.
BEKAPLAST—Corrosion-resistant lining systems. Atlas Minerals & Chemicals Inc.
BEL—Electroless nickel-boron plating process. Uyemura International Corp.
BELT MASTER—Backstand idlers. Formax Mfg. Corp.
BELTFLEX—Contact wheels. Munson Machinery Co. Inc.
BESBON—Cleaners, activators, accelerators, and plating processes for printed circuits. McGean-Rohco Inc.
BESPLATE—Copper, nickel, chromium, and brass plating processes. McGean-Rohco Inc.
BETA-KLEAN—Rigid structure depth filter. Cuno Inc.
BETAMIN—Backscatter thickness testing for precious metals. CMI International Corp.
BETASCOPE—Beta backsetter thickness gauge. Asoma-TCI
BI-MET—Black oxide conversion coating. Cleveland Black Oxide
BILOY—Multilayer nickel-iron plating process. Enthone-OMI Inc.
BIOACT—Cleaning solvents. Detrex Corp., Solvents and Environmental Services Div.
BIOACT—Semi-aqueous and organic solvents. Petroferm Inc.
BIOCAT—Metal cleaner. AIBP Inc.
BIPSUN—Flap wheel. Belanger Inc.
BISOSPRAY—Liquid buffing compound. Bison Corp.
BLACK ARMOR—Black chromate conversion coating. Atotech USA Inc.
BLACK GOLD—Chromate process to go over zinc or cadmium. Deveco Corp.
BLACK MAGIC—Dip drain paint. PPG Pretreatment & Specialty Products
BLACK ONYX—Black oxide process for heat-treated parts. Cleveland Black Oxide
BLACK PEARL—Decorative black nickel plating process. Enthone-OMI Inc.
BLACK TOPAZ—Cold jet-black finish for ferrous metals. Sur-Fin Chemical Corp.
BLACK VELVET—Black oxide coating. Henkel Surface Technologies
BLACKAT—Masking belt for selective plating machines. Fab-Tech
BLAKODIZE—Black treatment for steel. Luster-On Products Inc.
BLAST GARD—Line of blast cabinet parts. Pangborn Corp.
BLAST-O-LITE—Glass beads. Flex-O-Lite Div.
BLASTIMATICS—Wet and dry abrasive blasting equipment. Pressure Blast Mfg. Co. Inc.
BLASTITE—Aluminum oxide blasting media. Washington Mills Electro Minerals Corp.
BLASTKOTE—Mechanical impact zinc-iron alloy plating. Metal Coatings International Inc.
BLASTMASTER—Portable abrasive blaster. Kleer-Flo Co.
BLUE BLAZES—Bias-type mush buffs. Schaffner Mfg. Co. Inc.
BLUE GRIT—Coated abrasives. 3M Co., Abrasive Systems Div.
BLUE MAGIC—Buffing compound remover. Thermo-Cote Inc.
BLUE SUPER—Mush buff. Reliable Buff Co.
BLUE WAVE—Ultrasonic cleaning equipment. Blue Wave Ultrasonics
BLUE-CUT—Stainless steel buffing compound. Kocour Co. Inc.
BLUEAWAY—Cleaner to remove discoloration from steel. Competition Chemicals Inc.
BOBCAT—Composite-coated abrasive wheel. Schaffner Mfg. Co. Inc.
BOILERTROL—Contamination detector with steam trap. Belke Mfg. Co.
BOND-A-STRIKE—Alkaline electroless nickel strike. MacDermid Inc.
BONDAL—Alloy zincate for plating on aluminum. MacDermid Inc.
BONDERITE—Conversion coatings. Henkel Surface Technologies
BONDERLUBE—Reactive with zinc phosphate immersion coating. Henkel Surface Technologies
BONDETCH—Aluminum etchants. MacDermid Inc.
BOOTH KLEEN—Spray booth compound. Calgon Corp.
BOOTH KOTE—Paint detackifier. Stan Sax Corp.
BRADEX—Fiber abrasive tools. Abtex Corp.
BRASS-GLEAM—Brass plating process. Shipley Ronal
BRASS-GLO—High-speed brass plating process. Shipley Ronal
BRASS-MIR—Brass plating brighteners. Plating Resources Inc.
BRASSLUX—Bright brass plating process. MacDermid Inc.
BRAWLER—Diaphragm pump. Osmonics Inc.
BRENNER-SENDEROFF—Contractometer to measure stress in electrodeposits. Kameras Instruments
BRI-TIN—Bright acid tin plating process. Atotech USA Inc.
BRICBOND—Acid-proof cement. Ceilcote Air Pollution Control
BRILL—Chemical polish for brass, bronze, and copper. Arcal Chemicals Inc.
BRITE LINE—Drop-in PVC liner. F.C. Witt Associates Ltd.
BRITERITE—Abrasive disks and wheels. Standard Abrasives Inc.
BRONZAC—Noncyanide bronze plating process. Zinex Corp.
BRONZEBRITE—Bright bronze plating process. Puma Chemical
BRONZEX—Bronze plating process. Enthone-OMI Inc.
BRU-GAL—Phosphate prepaint treatment. Birchwood Laboratories Inc.
BRUISER—Blasting nozzle with tungsten carbide lining. Boride Products Inc.
BRUSHLON—Nylon fiber brush in wheel, disk, belt, cylinder, or sheet forms. 3M Co., Abrasive Systems Div.
BRUTE—Double-diaphragm corrosion-resistant pumps. Osmonics Inc.
BRUTUS—Corrosion-resistant pumps. Osmonics Inc.
BRY-CAD—Bright cadmium plating process. Enthone-OMI Inc.
BRYTE-ON—Acid tin plating process. Goldschmidt Industrial Chemical Corp.
BUBBLEGARD—Pneumatic liquid level control device. Cleveland Process Corp.
BUFCOM—Buffing compounds. Stan Sax Corp.
BUFCUT—Cord section power-driven brushes. Osborn International, A Unit of Jason Inc.
BUFF OFF—Metal cleaners. MacDermid Inc.
BUFF'N LIME—Buffing compounds. Kocour Co. Inc.
BUFFEX—Soak cleaning compounds. MacDermid Inc.
BUFSOFF—Buffing compound remover. Stan Sax Corp.
BUMPER NICKEL—Bright nickel plating process for bumpers. Atotech USA Inc.
BURNASHEEN—Burnishing compounds. McGean-Rohco Inc.
BURNS—Rouge buffing compounds. Matchless Metal Polish Co.
BURR BATCH—Vibratory finishing machine. Almco Inc.
BURR BENCH—Vibratory finishing machine. Abrasive Finishing Inc.
BURR BOWL—Small vibratory finisher. USFilter/VL Rampe
BUZZER—Gas burners and ovens. Charles A. Hones Inc.
BY-BUK—Plating masks. Shercon Inc.

C

CAD GLO—Cadmium plating process. Alchem Corp.
CAD-AID—Cadmium brightener and plating process. Pavco Inc.
CAD-MIR—Cyanide cadmium plating process. Plating Resources Inc.
CADVERT—Cadmium plating process. MacDermid Inc.
CALCUPLATE—Rectifier with software program. Sifco Selective Plating, Div. of Sifco Industries Inc.
CALORPLAST—PVDF heat exchanger. George Fischer Inc.
CANCEL—Fume suppressants. Plating Resources Inc.
CAPITOL—Three-phase heavy-duty rectifiers. American Plating Systems, Div. of Stewart Technologies Inc.
CAPLUGS—Masking plugs and studs. Duggan Masking Devices
CARB-OUT—Liquid chemical treatment system for removal of carbonates from cyanide plating baths. Accurate Engineering Labs, Div. of Rin Inc.
CARBO-COR—Degreaser recycling system. Koch Membrane Systems Inc.
CARBO-CUT—Nonwoven finishing abrasives. Carborundum Abrasive Co.
CARBO-DUR—Activated carbon. USFilter/Permutit
CARBO-KLEAR—Carbon purification system for depth filtration and carbon treating plating solutions. Summit Scientific Corp.
CARBOLATOR—High capacity carbon treating and filtration system. Sethco Div., Met-Pro Corp.
CARBOLON—Silicon carbide polishing grain. Exolon-ESK Co.
CARBOLUX—Contaminant removal system for plating baths. USFilter/JWI
CAROUSEL—Self-cleaning backwash filter. Summit Scientific Corp.
CASH REGISTER—Device for measuring the deposit of a metal from a plating bath. Technic Inc.
CASTBRITE—Liquid concentrate used with nitric acid for bright dipping of zinc. MacDermid Inc.
CATA-DYNE—Gas-fired infrared heater. Ciscan Industries Ltd.
CATAPOSIT—Liquid catalyst for plating on plastic. Shipley Ronal
CATAPREP—Liquid catalyst additive for plating on plastic. Shipley Ronal
CATHODICOTE—Cathodic electrocoating system. George Koch Sons LLC
CATHOSPHERES—Precision copper-plated plastic balls for barrel plating. Plastic Methods Co.
CAUSPLIT—Acid- and alkali-resistant cement. Elf Atochem North America Inc.
CAVIDERM—Nondestructive plated through-hole tester. Veeco Industrial Measurement
CECARBON—Granular activated carbon. Elf Atochem North America Inc.
CEIL-BRITE—Bright acid sulfate tin plating process. Ames Metal Products Co.
CEIL-MATTE—Acid sulfate tin plating process. Ames Metal Products Co.
CEILCRETE—Glass-reinforced polyester lining. Ceilcote Air Pollution Control
CENTECH—Centrifugal system for clarifying mass-finishing wastewater. Barrett Centrifugals Inc.
CENTURION—Control for paint finishing systems. Precision Quincy Corp.
CERAMCELL—Ceramic plating cell. Larry King Corp.
CERATREX—Microporous ceramic filters. Osmonics Inc.
CERFA-KLEEN—Metal cleaning compounds. Houghton International Inc.
CHALLENGER—Flap wheels. Belanger Inc.
CHANNEL SLOPE—Polymer concrete drain systems. ACO Polymer Products Inc.
CHEC-MATE—Automatic metering pump. Hoover Container Sales & Service Inc. Sub. of Hoover Group Inc.
CHECK-LINE—Coating thickness tester. Electromatic Equipment Co. Inc.
CHELUX—Copper and brass plating processes. JacksonLea, A Unit of Jason Inc.
CHEM CLEAN—Oil splitting and emulsifying cleaners. Brent America Inc.
CHEM COTE—Iron and zinc phosphate conversion coatings. Brent America Inc.
CHEM CREST—Ultrasonic cleaning chemicals. Crest Ultrasonics Corp.
CHEM GUARD—Chemical feeder. HBS Equipment Corp.
CHEM SEAL—Sealing rinses. Brent America Inc.
CHEM-CLAMP—Stainless steel anodizing clamp. Anodic Inc.
CHEM-FLOC—Paint detackifier. Brent America Inc.
CHEM-GARD—Plastic centrifugal pump. Vanton Pump & Equipment Corp.
CHEM-GRIT—Corrosion-resistant nonslip floor. Composite Structures Int'l. Inc. (CSI)
CHEM-POLISH—Bright dips for ferrous and nonferrous metals. Shipley Ronal
CHEM-SAFE—Double-trench drain system. ACO Polymer Products Inc.
CHEMAX—Conversion coatings for zinc, cadmium, and brass. Pax Surface Chemicals Inc.
CHEMBOND—Alkaline and acid cleaning and surface preparation compounds. Pax Surface Chemicals Inc.
CHEMBURR—Acid deburring compound. Heatbath Corp.
CHEMCOTE—Coating and passivation processes. Pax Surface Chemicals Inc.
CHEMDUTY—Corrosion-resistant pumps. R-V Industries Inc.
CHEMESTER—Vinyl ester resin for floor topping. Atlas Minerals & Chemicals Inc.
CHEMFLUOR—Fluoropolymer diaphragm valve. Norton Performance Plastics Corp.
CHEMFOS—Phosphate coating process. Pax Surface Chemicals Inc.
CHEMIDIZE—Aluminum surface process. MacDermid Inc.
CHEMOMAT—Electrodialysis metal recovery system. Ionics Inc., Separations Technology Div.
CHEMSEAL—Surface sealers for phosphates. Pax Surface Chemicals Inc.
CHEMTOOL—Electrochemical deburring process. Dynetics Corp.
CHEMTRED—Fiberglass-reinforced polyester stair treads. Composite Structures Int'l. Inc. (CSI)
CHEMTROL—Mass-finishing compounds. Precision Finishing Inc.
CHEMTURION—Chemical protective suit. ILC Dover Inc.
CHLOR-ALARM—Chlorine gas detector alarm. Chlorinators Inc.
CHLOROMAX—Acid zinc plating processes. Chemtech Finishing Systems Inc.
CHLOROSCRUB—System for neutralizing and scrubbing released gases. Tri-Mer Corp.
CHLOROSTAR—Bright acid zinc process. Starlite Technical Service Inc.
CHLOROTHENE—1,1,1-trichloroethylene degreasing solvent. Dow Chemical Co.
CHRO-MIR—Chromate conversion coatings. Plating Resources Inc.
CHROM-A-DYE—Chromate and dye process. Pavco Inc.
CHROMALL BRIGHT—Decorative and hard chromium plating processes. Starlite Technical Service Inc.
CHROMAPUR—Ion exchange system for hard chromium plating. Eco-Tec Inc.
CHROMATIC—Process for automatic treatment of chromium rinse waters. Aqualogic Inc.
CHROMAX—Catalyst additives for chromium plating. Pax Surface Chemicals Inc.
CHROMAX—Conversion coatings for zinc plate. Chemtech Finishing Systems Inc.
CHROMAX—Trivalent irridescent chromate for zinc plate. MacDermid Inc.
CHROMEKILL—Reducing compound for hexavalent chromium. Enthone-OMI Inc.
CHROMESCRUB—Fume scrubber for chromium plating baths. Tri-Mer Corp.
CHROMETEX—Nickel activator. MacDermid Inc.
CHROMEVERT—Chromate conversion coatings. American Chemical & Equipment
CHROMICOAT—Conversion coating for aluminum and zinc. Oakite Products Inc., A Member of The Chemetall Group
CHROMITING—Trivalent chromium passivation for zinc and zinc alloys. Continental Surface Treatment Inc.
CHROMOUT—Process for reducing hexavalent chromium. Kentucky Water Treatment Co. Inc.
CHROMOX—Ion exchange system for hard chromium plating. Eco-Tec Inc.
CIMATIC—Aqueous parts cleaning system. Cincinnati Industrial Machinery, Div. of Eagle Picher Industries Inc.
CIRCUITPREP—Cleaning and surface conditioning process for circuit boards. Enthone-OMI Inc.

CIRCUTRON—Preplate processes for printed circuit boards. Atotech USA Inc.

CITRANOX—Manual or ultrasonic phosphate-free acid cleaner. Alconox Inc.

CITRIDET—Natural solvent cleaner. Oakite Products Inc., A Member of The Chemetall Group

CITRISURF—Citric acid based cleaning and passivation material. Stellar Solutions Inc.

CLAIR—Polishing and buffing machinery. McKean Machinery Sales Inc.

CLAR-O-FLOC—Flocculating clarifier. Alar Engineering Corp.

CLARIFUGE—Centrifuge. Barrett Centrifugals Inc.

CLAROSTAN—Purifier for sulfate tin baths. Shipley Ronal

CLEAN AND STRIP—Abrasive-impregnated nonwoven disks and wheels. 3M Co., Abrasive Systems Div.

CLEAN-O-MATIC—Parts washer. Graymills Corp.

CLEANMASTER—Parts washer. Kleer-Flo Co.

CLEANOFF—High-speed soak cleaner. JacksonLea, A Unit of Jason Inc.

CLEANOL—Electrocleaner for steel. JacksonLea, A Unit of Jason Inc.

CLEAR-CUT—Plastic blast media for cleaning soft metals. Composition Materials Co. Inc.

CLEARCLAD—Electrophoretically-applied clear coat. Clearclad Coatings Inc.

CLEARLYTE—Cathodically-applied polymer coating process. Enthone-OMI Inc.

CLEP ETCH A—Acid activator. MacDermid Inc.

CLEP-A-LAQ—Water-based lacquers. MacDermid Inc.

CLEPCO—Electric immersion heaters, liquid level controls, and infrared ovens. Cleveland Process Corp.

CLEPO—Cleaning compounds, surface treatments, plating processes, and strippers. MacDermid Inc.

CLEVELAND—Compact top-entry mixers. EMI Inc.

CLIP-EYELET—Spray nozzle. Spraying Systems Co.

CLYDESDALE—Pumps and filters. Camac Industries

CO-BRA-ETCH—A preplate etchant. Electrochemicals

CO-BRA-SOL—Copper and brass bright pickle. Electrochemicals

CO-ORDINATOR—Remote control monitoring equipment for wastewater systems. DMP Corp.

COBRE—Alkaline, noncyanide copper plating process. Mibus Inc.

COBRE—Noncyanide copper plating process. Zinex Corp.

COLAG—Fume scrubber. Snyder General Corp. American Air Filter

COLD TRAP—Solvent recovery equipment. Ultra-Kool Inc.

COLD VAPORIZATION—Vacuum distillation wastewater recovery system. Calfran International Inc.

COLEC—Alkaline electrocleaner. MacDermid Inc.

COLOR-CHEX—Color matching tool. Atlas Electric Devices Co.

COLORSPEEDER—Equipment for fast color change in powder coating. ITW Gema

COLZINC—Alkaline noncyanide zinc plating process. Columbia Chemical Corp.

COMBIPOSIT—System for producing printed circuit boards. Shipley Ronal

COMBO—Abrasive flap wheel. Schaffner Mfg. Co. Inc.

COMPOBOND—Acid-proof cement. Ceilcote Air Pollution Control

COMPRESS—Polishing wheels. Munson Machinery Co. Inc.

COMPUDERM—Computerized coating thickness gauge. Veeco Industrial Measurement

COMPUPAK—Computer-controlled power systems. Trilectron Industries Inc.

CONDOR—Abrasive belts, disks, and flap wheels. Merit Abrasive Products Inc.

CONDUCTRON—A direct metallization system for printed circuit board fabrication. Shipley Ronal

CONFORMASK—Solder mask. Morton Electronic Materials Morton International Inc.

CONSEP—Crossflow membrane filtration system. Koch Membrane Systems Inc.

CONTINUOUS-FLO—Blast cleaning machines. Pangborn Corp.

CONTROLSTIK—Automatic rinse control system. Myron L Co.

COOL-PHOS—One-stage nonaqueous degreasing and phosphating process. Metal Coatings International Inc.

COPKIA RIP—Immersion-type metal strippers. Uyemura International Corp.

COPPER GLEAM—Bright acid copper plating process. Shipley Ronal

COPPER GLO—Bright cyanide copper plating process. Shipley Ronal

COPPER GLO—Copper plating process. Alchem Corp.

COPPERLUME—Copper plating process. Atotech USA Inc.

COPPERMERSE—Electroless copper plating system. Shipley Ronal

COPRITE—Brightener for copper and brass plating baths. Accurate Engineering Labs, Div. of Rin Inc.

CORCLENE—Alkaline cleaner. Coral Chemical Co.

CORFLOAT—Water-wash spray booth compound. Coral Chemical Co.

CORLAR—Epoxy enamels and primers. DuPont Co.

COROLINE—Reinforced epoxy lining and flooring. Ceilcote Air Pollution Control

CORRASIL—Topcoats for chromates. Atotech USA Inc.

CORSEAL—Rust and corrosion inhibitors. Tronex Chemical Corp.

CORZAN—Chemical-resistant piping systems made from CPVC. BFGoodrich Co., Corzan Industrial Systems Div.

COSMOLINE—Rust preventives. Houghton International Inc.

COTE D'OR—Heavy gold electroplate. Technic Inc.

COTIN—Alternative undercoat to replace nickel prior to gold plating. Zinex Corp.

COULODERM—Thickness gauge for use on very small areas. Veeco Industrial Measurement

COULOSCOPE—Coulometric coating thickness gauge. Fischer Technology Inc.

COULOTEST—Coulometric thickness tester. Asoma-TCI

COURIER—Multistream on-line analyzer for plating baths. Metorex Inc.

CRAP TRAP—Rubber-bottom anode bag. Anode Products Co. Inc.

CRITERION—Nickel plating process. Taskem Inc.

CROMYLITE—Decorative chromium plating processes. Enthone-OMI Inc.

CROSS-CUT—Airless spray paint nozzle. Nordson Corp., Liquid Systems Group

CROSSFIRE—Open-weave abrasive disk. Even Cut Abrasive Co.

CROWBAR—System of spark protection for electrostatic painting. ITW Ransburg Electrostatic Systems

CROWN—Plating equipment, exhaust systems, and rectifiers. Atotech USA Inc.

CROWNGOLD—Gold strike for plating onto stainless steel. Engelhard Electro Metallics Div.

CROWNS—Electrolytic nickel anodes. Falconbridge U.S. Inc.

CRYSCOAT—Process for cleaning and phosphating steel, aluminum, zinc, and other metals before painting. Oakite Products Inc., A Member of The Chemetall Group

CRYSTOLON—Silicon carbide abrasive for polishing; also grinding wheels and refractories. Norton Co.

CTROL—Bright nickel plating additive. Chemtech Finishing Systems Inc.

CU-BRITE—Electrolytic roll-forged copper anodes. Univertical Corp.

CU-MIR—Bright cyanide copper plating process. Plating Resources Inc.

CU-PHOS—High phosphorus roll-forged copper anodes. Univertical Corp.

CU-TRONIX—Acid copper plating process for through-holes. Atotech USA Inc.

CUBATH—Acid copper plating bath. Enthone-OMI Inc.

CUBOND—Alkaline noncyanide copper plating process. MacDermid Inc.

CUBRITE PLUS—Copper addition agents for both cyanide and acid. A Brite Co.

CUDEC—Acid copper plating process. Shipley Ronal

CUFLEX—Acid bright copper plating processes. McGean-Rohco Inc.

CULMO—Bright tin plating process. Dr. Ing. Max Schlotter

CUMAC—Acid copper plating processes. MacDermid Inc.

CUPOSIT—Electroless copper plating process. Shipley Ronal

CUPPS—Bright acid copper plating process. Plating Process Systems Inc.

CUPRACID—Acid copper plating process for decorative and circuit board applications. Atotech USA Inc.

CUPRAFIN—Bright acid copper plating process. MacDermid Inc.

CUPRAKOTE—Immersion copper plating process. Heatbath Corp.

CUPRAL—Alkaline noncyanide copper plating process. Enthone-OMI Inc.
CUPRALITE—Cyanide copper plating plating process. Enthone-OMI Inc.
CUPREX—Semibright acid copper plating system for circuit boards. Atotech USA Inc.
CUPRINT—Acid copper plating process. Enthone-OMI Inc.
CUPROBOND—Copper immersion plating process. Henkel Surface Technologies
CUPRODINE—Immersion copper coating for steel. Henkel Surface Technologies
CUPRON—Alkaline cyanide-free copper alloy plating process. Shipley Ronal
CUPROSTAR—Bright acid copper plating process. Starlite Technical Service Inc.
CUPURE—Cyanide-free copper plating process. Shipley Ronal
CURVABLAST—Abrasive blasting cabinet. Pangborn Corp.
CUSTAN—Immersion tin plating process. Atotech USA Inc.
CUSTRIKE—Alkaline copper plating process. Atotech USA Inc.
CUSTRIKE—Alkaline noncyanide copper strike process. MacDermid Inc.
CUTROL—Cyanide copper plating process. Plating Resources Inc.
CY-AN-IN—Indium cyanide plating process. Indium Corp. of America
CY-LESS—Noncyanide bright silver, gold, and copper strikes. Technic Inc.
CYCLEMASTER—Automatic plating machine. Enthone-OMI Inc.
CYCLO-ETCH—Sulfuric peroxide etchant. Electrochemicals
CYCLOJET—Parts washer. Better Engineering Mfg. Inc.
CYCLONE—Parts washer. Midbrook Inc.
CYLSONIC—Ultrasonic cleaning unit. Rosemont Analytical
CYNOREX—High-speed bright cyanide copper plating process. Atotech USA Inc.
CYSTRIP—Plastic blasting media. AC Molding Compounds

D

D SMUT—Chromate-type deoxidizer. DuBois, Div. of Diversey Lever
D-FOAMER—Foam reducing agent. Pax Surface Chemicals Inc.
D-TARNISH—Tarnish remover and protector for silver, brass, copper, and tin. Pax Surface Chemicals Inc.
D-ZOLVE—Immersion paint stripper. Solvent Kleene Inc.
DACROMET—Water-based dispersion coating based on chromium and zinc. Metal Coatings International Inc.
DAFTEX—Dissolved air flotation system for oil and water separation. Hoffland Environmental Inc.
DAISY—Deburring wheel. Bison Corp.
DALIC—Selective plating processes and equipment. Sifco Selective Plating, Div. of Sifco Industries Inc.
DANIELS—Plating barrels. Napco Inc.
DARACLEAN—Aqueous cleaner. Detrex Corp., Solvents and Environmental Services Div.
DARACLEAN—Aqueous metal cleaner. W.R. Grace & Co.
DE-TAK—Batch treatment process for spent photoresist strippers. Romar Technologies Inc.
DEBURGH—Conveyors. George Koch Sons LLC
DECALUME—Bright acid copper plating process. Atotech USA Inc.
DECOATER—Nonpolluting nonhazardous paint stripper. Pavco Inc.
DECOR—Decorative acid gold plating process. Technic Inc.
DECORAL—Conversion coating coloring process. JacksonLea, A Unit of Jason Inc.
DECOREX—Palladium plating process. Enthone-OMI Inc.
DEFOAM—Foam reducer. Pax Surface Chemicals Inc.
DEGREASOL—Cleaning solvent. Kleer-Flo Co.
DEL-MONOX—Air filter for compressed air lines. Deltech Engineering Inc.
DELTA-SCOPE—Nondestructive coating thickness gauge. Fischer Technology Inc.
DELTA-STAK—Clarifiers. Eimco Process Equipment Co.
DENAMEL—Porcelain enamel stripping process. Kolene Corp.
DEOXIDE—Oxide and smut removal for aluminum. Heatbath Corp.
DEOXIDINE—Metal cleaner, rust remover. Henkel Surface Technologies
DEOXYLYTE—Additive for rinse baths. Henkel Surface Technologies
DERMALOY—White bronze plating process. Atotech USA Inc.
DERMITRON—Nondestructive coating and plating thickness gauge. Veeco Industrial Measurement
DERUSTAL—Alkaline derusting compounds. Heatbath Corp.
DET-O-JET—Degreaser. Alconox Inc.
DETRIDE—Cleaning solvents. Detrex Corp., Solvents and Environmental Services Div.
DEV-KLEEN—Spray wash cleaner. Deveco Corp.
DEV-KOTE—Zinc phosphate coating. Deveco Corp.
DEVILUX—Paint pump. ITW Ransburg Electrostatic Systems
DEVLAC—Air-dry and thermosetting water-soluble lacquers. Deveco Corp.
DEVSTAR—Chromium, electroless nickel, and brass plating processes. Deveco Corp.
DI-AQUA—Alkylaryl sulfonate surface active agent. Metal Coatings International Inc.
DIAMOND CROSSCUT—Contact wheel. Matchless Metal Polish Co.
DIAMOND JET—Metal spray oxy fuel gun. Metco Div., Perkin-Elmer
DICUT—Zinc diecasting buff compounds. Kocour Co. Inc.
DIGI-PLATE—Pulse plating power supplies. Dynatronix Inc.
DIGICHEM—Automated analysis of metals in bath components. Ionics Inc., Separations Technology Div.
DIGITROL—pH recorder-controller with digital read-out. Analytical Measurements Inc.
DIP-PAK—Hot melt peelable plastic coating. OMG Fidelity
DIPLOMAT—Solid state line of rectifiers. American Plating Systems, Div. of Stewart Technologies Inc.
DIRECTOR—Hoist controller. Plasfab Inc.
DISC TURBO—Centrifugal high-speed mass-finishing machine. Dreher Corp.
DISC-CENTER—Knot-style brushes. Osborn International, A Unit of Jason Inc.
DISPENSO—Drum hand truck and drain stand. Morse Mfg. Co. Inc.
DIVCO—Lead, tin, and solder anodes. Division Lead Ltd. Partnership
DIVERCLEAN—Alkaline cleaners. Chemtech Finishing Systems Inc.
DIWALYT—Acid tin and tin-lead bath for circuit boards. Atotech USA Inc.
DOG BONE—Silver anodes. Engelhard Electro Metallics Div.
DOUBLE-BOND—Iron phosphate. Calgon Corp.
DOWEX—Ion exchange resins. Dow Chemical Co.
DRAGONITE—Solid glass balls. Jaygo Inc.
DRI TOUCH—Water-displacing rust preventive. Birchwood Laboratories Inc.
DRIOIL—Protective dip coating. Pax Surface Chemicals Inc.
DROPOUT—Wastewater precipitation agent. A Brite Co.
DRUM-KARRIER—Below-the-hook lifter for drums. Morse Mfg. Co. Inc.
DRY BLAST—Abrasive blasting equipment. Vapor Blast Mfg. Co.
DRY STEAM—Electric portable steam generator. Electro-Steam Generator Corp.
DRY-PAK—Lightweight, solid dielectric power supply for electrostatic coating. ITW Ransburg Electrostatic Systems
DUAL-MATIC—Programmed hoist programmable by speaking to the controller. PMS Inc.
DUAL-O-MATIC—Plating rectifier and a reversing switch. Clinton Power, Subsidiary of Benjamin Power Co.
DUALSCOPE—Hand-held coating thickness gauge. Fischer Technology Inc.
DUCHROME—Chromate conversion coatings. MacDermid Inc.
DUCKBILL—Sampling device for wastewater. Markland Specialty Engineering Ltd.
DUCLEAN—Alkaline cleaners. MacDermid Inc.
DULCOMETER—pH, chlorine residual, and conductivity monitoring system. ProMinent Fluid Controls Inc.
DULUX—Enamels, finishes, thinners, varnishes, paints. DuPont Co.
DUMATIC—Electropolishing equipment. HBS Equipment Corp.
DUO-DOOR—Slide-locking plating barrel. Atotech USA Inc.
DUO-FINE—Pleated microfiberglass filter cartridge. USFilter/Filterite
DUOZINC—Cyanide zinc plating processes. McGean-Rohco Inc.
DUPHOS—Iron and zinc phosphate coatings. MacDermid Inc.
DUPLALUX—Bright and semibright nickel plating processes. Atotech USA Inc.
DUR-NI—Bright nickel plating process. Enthone-OMI Inc.
DURA-CLEAN—Alkaline cleaners. Plating Resources Inc.

DURA-DANGLERS—Plating barrel electrical contracts. Singleton Corp.
DURA-FLEX—Cup brush. Osborn International, A Unit of Jason Inc.
DURA-GARD—Iron phosphating compounds. DuBois, Div. of Diversey Lever
DURA-LIFE—Plastic tanks. Kerrco Inc.
DURABOND—Primer system to promote adhesion of prepreg to copper. McGean-Rohco Inc.
DURACHROME—Chromium plating processes. Plating Resources Inc.
DURACLAMP—Anodizing clamp. Burlingham International
DURACOAT—Chromate conversion coatings for cadmium, copper, and zinc. Heatbath Corp.
DURACOR—Synthetic plastic compound for ducts, hoods, tanks, etc. Ceilcote Air Pollution Control
DURACRON—Acrylic enamel finishes. PPG Industries Inc.
DURACYCLE—Electroless nickel plating process. Shipley Ronal
DURAFET—Solid-state pH electrode. Leeds & Northrup, A Unit of General Signal
DURAFLOOR—Raised flooring system. Morrison Molded Fiber Glass Co.
DURALAK—Protective clear coating. Heatbath Corp.
DURALITE—Lightweight ceramic mass finishing media. Washington Mills Ceramics Corp.
DURALOK—A locking anodizing torque tool. Burlingham International
DURALUM—Tumbling nuggets. Washington Mills Ceramics Corp.
DURAMEDIA—Preformed tumbling shapes. Washington Mills Ceramics Corp.
DURANAR—Pigmented fluorocarbon coatings. PPG Industries Inc.
DURAPHRAM—Long-life diaphragms. Osmonics Inc.
DURAPOSIT—Electroless nickel plating processes. Shipley Ronal
DURAPREP—Plating pretreatment cleaners and activators. Shipley Ronal
DURASTRIP—Paint strippers. Heatbath Corp.
DURATREX—Stainless steel filters. Osmonics Inc.
DURISOL—Iron phosphate coating for steel. Henkel Surface Technologies
DUST-HOG—Dust collection system. United Air Specialists Inc.
DUSTKOP—Dust collector. Aget Mfg. Co.
DUSTLOK—Dual-density tackified filter media. Fiber Bond Corp.
DUXBAK—Water-displacing rust preventive. MacDermid Inc.
DUZINC—Zinc plating brightener. MacDermid Inc.
DYCLENE—Reverse current cleaner for diecastings. MacDermid Inc.
DYGLEAM—Process for zinc diecastings. MacDermid Inc.
DYNA-PULSE—Pulse plating module for rectifiers. Dynatronix Inc.
DYNABLAST—Pressure blasting abrasive. Norton Co.
DYNADET—Alkaline tank cleaner. Oakite Products Inc., A Member of The Chemetall Group
DYNAFILE—Abrasive belt machine. Dynabrade Inc.
DYNAFLOW—Low pressure abrasive flow finishing. Dynetics Corp.
DYNAMASK—Dry film solder mask. Morton Electronic Materials *Morton International Inc.*
DYNAPLATE—Electroless copper plating process. Morton Electronic Materials Morton International Inc.
DYNAPUMP—Nonmetallic pump. Crane Co., Chempump Div.
DYNASAND—Continuous sand-filtration unit. Parkson Corp.
DYNATROL—Viscosity measurement and control system. Automation Products Inc.

E

E-BRITE—Plating brighteners and addition agents. Electrochemical Products Inc. (EPI)
E-KLEEN—Metal cleaners. Electrochemical Products Inc. (EPI)
E-PHOS—Iron, manganese, and zinc phosphate coating processes. Electrochemical Products Inc. (EPI)
E-POX-Z—Paint stripper. Elf Atochem North America Inc.
E-PREP—Bright dips. Electrochemical Products Inc. (EPI)
E-TECH—Acid salts, deoxidizers, desmutters, etchants, rust preventives, and corrosion inhibitors. Electrochemical Products Inc. (EPI)
E-Z TREAT—Batch treatment process for spent electroless copper solutions. Romar Technologies Inc.
EAGLE—Portable eddy current test instrument. Uniwest
EASTERN—Mixing equipment. EMI Inc.
EBONOL—Blackening processes for copper and zinc. Enthone-OMI Inc.
ECLIPSE—Vacuum plating equipment. Materials Research Corp.
ECLIPSE—Wastewater polymers. Calgon Corp.
ECO-NODE—Insoluble anode for a metal recovery system. Eco-Tec Inc.
ECOCLEAN—Cleaning machines. Durr Ecoclean
ECOLOSID—Potassium zinc chloride plating process. McGean-Rohco Inc.
ECOLOZINC—Acid and alkaline cyanide-free zinc plating processes. McGean-Rohco Inc.
ECON-E-COAT—Electrocoat paint finishing systems. Therma-Tron-X Inc.
ECON-E-LAB—Modular laboratory unit for finishing systems. Therma-Tron-X Inc.
ECONO COLOR—Two-step coloring process for anodized aluminum. Goldschmidt Industrial Chemical Corp.
ECONO SORB—Spill absorbents. Osborn International, A Unit of Jason Inc.
ECONO-CHROME—Chromium plating processes. McGean-Rohco Inc.
ECONO-COAT—Powder spray booth system. Nordson Corp., Liquid Systems Group
ECONO-FINISH—Abrasive blasting cabinet. Empire Abrasive Equipment Co.
ECONO-SOLV—Solvent vapor recovery system. Detrex Corp., Equipment Div.
ECONO-TREAT—Packaged waste treatment systems. USFilter/Warrendale
ECONOCOIL—Plate-type heat exchanger. Tranter Inc.
ECONOMEDIA—Ceramic mass-finishing media. Almco Inc.
ECONOSTRIP—Paint stripper. Sur-Fin Chemical Corp.
ECOSORB—Adsorptive precoat filter media. Graver Technologies Inc.
ECOVAC—Vacuum deoiling system. Ipsen International Inc.
EDCOR—Flushable, tubular anode membrane. Koch Membrane Systems Inc.
EDDY-MAG—Coating thickness tester. CMI International Corp.
EDGE MASTER—Edge finishing and deburring tool. Finishing Associates Inc.
EKASIT—Metal cleaners. JacksonLea, A Unit of Jason Inc.
EKOLASID—Cyanide-free bright chloride zinc plating processes. McGean-Rohco Inc.
ELCA—Line of twin bed deionizers. USFilter/IWT
ELECTRO-BRITE—Zinc plating processes, conversion coatings, bright dips, and cleaners. *Electrochemicals*
ELECTRO-KLEEN—Heavy-duty powdered electrolytic cleaner. Heatbath Corp.
ELECTROBLACK—Black plating process. Enequist Chemical Co. Inc.
ELECTROCARB—Black silicon carbide blasting media. Electro Abrasives Corp.
ELECTROLYZER—Electrowinning apparatus. USFilter/JWI
ELECTROM&T—Electrolytic cleaners. Atotech USA Inc.
ELECTROMNI—A quarter-actuated ball valve. Asahi/America Inc.
ELECTROPOSIT—Electrolytic plating products. Shipley Ronal
ELECTROPURE—Fluoborates for printed circuitry. Atotech USA Inc.
ELECTROSOLV—Modified tartrate additive for cyanide solutions. Electrochemical Products Inc. (EPI)
ELEKTRA—Bright acid copper plating process. Atotech USA Inc.
ELIMA-MATIC—Air-operated double-diaphragm pumps. Versa-Matic Pump Co.
ELIMINATOR—Portable mass-finishing machine. Rosemont Industries Inc.
ELIMINOX—Scrubbing system. Duall Div., Met-Pro Corp.
ELNIC—Electroless nickel plating processes. MacDermid Inc.
EMULSONATOR—Emulsion cleaning and waste treatment system. Electronic Controls Design Inc.
ENBO—Electroless nickel-boron plating process. Surface Technology Inc.
ENBOND—Alkaline cleaners for a variety of metals. Enthone-OMI Inc.
ENCAPSOL-8—Flocculating agent. Advanced Chemical Co.
ENCAPSULATOR—Filtration system for compressed air lines. La-Man Corp.
ENCLAD—Process for selective plating of metals on ceramics. Enthone-OMI Inc.

ENDOVER—Drum tumbler and mixer. Morse Mfg. Co. Inc.
ENDOX—Alkaline compounds for removing rust and scale from iron and steel. Enthone-OMI Inc.
ENDURA GLO—Gold plating process. Shipley Ronal
ENDURION—Phosphate coating for ferrous metals. Jackson-Lea, A Unit of Jason Inc.
ENDUROPREP—Phosphate coating systems. JacksonLea, A Unit of Jason Inc.
ENERGY MASTER—Fiberglass-reinforced plastic packed-bed fume scrubbers and fans. Harrington Industrial Plastics Inc.
ENEROX—Water-based alkaline cleaner. Enequist Chemical Co. Inc.
ENERSCAN—Vapor concentration controller for bake ovens. Despatch Industries Inc.
ENFINITY—Electroless nickel plating system. Stapleton Technologies
ENFORCER—Closed-loop evaporator system. Midwest Air Products Co. Inc.
ENGILD—Decorative gold plating processes. Engelhard Electro Metallics Div.
ENGOLD—High-speed acid gold plating process. Engelhard Electro Metallics Div.
ENHANCE—Cleaning additive. Oakite Products Inc., A Member of The Chemetall Group
ENLOY—Cobalt alloy plating process. Enthone-OMI Inc.
ENLUBE—Additive for producing electroless nickel composite coatings. Enthone-OMI Inc.
ENPAX—Electroless nickel-phosphorus plating system. Pax Surface Chemicals Inc.
ENPLATE—Electroless copper and nickel plating processes. Enthone-OMI Inc.
ENPREP—Surface preparation processes. Enthone-OMI Inc.
ENSEAL—Corrosion-resistant sealants for zinc and zinc alloys. Enthone-OMI Inc.
ENSHIELD—Electroless plating process for EMI/RFI shielding. Enthone-OMI Inc.
ENSLIP—Electroless nickel composite coating with Teflon. Plating Process Systems Inc.
ENSTAT—Passivation system for electroless nickel plating. Palm Commodities International Inc.
ENSTRIP—Selective metal stripping processes. Enthone-OMI Inc.
ENTEK—Corrosion-resistant filters. Asahi/America Inc.
ENTEK—Processes for tarnish, corrosion, and stain protection. Enthone-OMI Inc.
ENTHOBRITE—Brighteners for zinc, cadmium, and copper. Enthone-OMI Inc.
ENTHOL—Emulsion and solvent cleaners. Enthone-OMI Inc.
ENTHOX—Chromate conversion coatings. Enthone-OMI Inc.
ENVIRO-DRI—Steam-operated sludge dryer. Duriron Co. Inc., Engineered Systems Group
ENVIRO-SAFE—Electrolytic recovery system. RRC Agmet Inc.
ENVIRO-VAP—Wastewater evaporation system. EnviroSystems Inc.
ENVIROCHROME—Trivalent chromium plating process. MacDermid Inc.
ENVIROMASTER—Electrowinning cell. BEWT Systems Inc.
ENVIROMAT—Membrane filtration systems. Ionics Inc., Separations Technology Div.
ENVIRON—Water-reducible coatings. PPG Industries Inc.
ENVIROSTRIP—Electrolytic metal stripper. Technic Inc.
ENVIROSTRIP—Paint strippers. MacDermid Inc.
ENVIROZIN—Alkaline zinc electroplating process. MacDermid Inc.
ERECTOVEN—Infrared drying and curing oven. Cleveland Process Corp.
ERGO-BLAST—Blast cleaning cabinet. Empire Abrasive Equipment Co.
ET JUNIOR—Evaporative tank. Poly Products Corp.
ETERNA GLO—Gold-silver alloy plating process. Shipley Ronal
ETERNITY—Anode hook for acid sulfate tin plating. Ames Metal Products Co.
EURO-ETCH—Aluminum etch regeneration systems. Eco-Tec Inc.
EUROPRESS—Plate-and-frame or diaphragm filter presses. Summit Scientific Corp.
EUROSTRIP—Paint stripping process. Oakite Products Inc., A Member of The Chemetall Group
EURROMATIC—Hollow plastic balls. Techne Inc.
EVERLUBE—Bonded solid film lubricant. E/M Engineered Coating Solutions
EVERON—Regenerative electroless nickel plating process. Shipley Ronal
EVERSHIELD—Nickel, copper, and graphite conductive paints. E/M Engineered Coating Solutions
EVERSOFT—Tack cloth. Louis M. Gerson Co.
EVERTUF—Plating barrels. Engelhard Electro Metallics Div.
EXCALIBUR—Nickel plating process. Enthone-OMI Inc.
EXCEL—Powder coating spray booth. Nordson Corp., Liquid Systems Group
EXCELINE—Flexible PVC tank liner. F.C. Witt Associates Ltd.
EXO-SPHERE—Abrasive blasting media. Exolon-ESK Co.
EXPRAY—Spray cleaners. Chemtech Finishing Systems Inc.
EXXATE—Degreasing solvent. Exxon Chemical Co.
EZ LIFT—Hook for titanium anode baskets. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
EZE-PEEL—Dry mask material. Calgon Corp.

F

FADE-OMETER—Laboratory device for sunfastness tests. Atlas Electric Devices Co.
FAILSAFE—Quartz immersion heater. Cleveland Process Corp.
FASCOLOR—Electropainting process. Uyemura International Corp.
FASCUT—Treated tampico section wheels. Osborn International, A Unit of Jason Inc.
FAST FINGER PLATER—Table-top gold plating console. Technic Inc., Equipment Div.
FASTBLAST—Aluminum oxide blasting grain. Exolon-ESK Co.
FASTRIP—Plastic media dry stripping machine. Empire Abrasive Equipment Co.
FERRODEX—Electrocleaning solutions. Atotech USA Inc.
FERROGUARD—Phosphate coating process. Alchem Corp.
FERROHONE—Polishing compound for steel. Aldoa Co.
FERROLYTE—Metal cleaners. Starlite Technical Service Inc.
FERROMIL—A chemical accelerator for mass finishing. REM Chemicals Inc.
FIBERGRATE—Fiberglass-reinforced floor grating. Composite Structures Int'l. Inc. (CSI)
FIBRAL—Compressed steel for scrubbing printed circuit boards. JacksonLea, A Unit of Jason Inc.
FIDELEX—Metal stripper. OMG Fidelity
FIDELPLATE—Electroless plating solutions. OMG Fidelity
FILMITE—Spray booth coating. DuBois, Div. of Diversey Lever
FILTA-PURE—Proportionable filter carbon treater in a single chamber. Summit Scientific Corp.
FILTERMATIC—Automatic filter systems. Summit Scientific Corp.
FILTERYTE—Photoresist stripper. Sweet Chemical Services Co. Inc.
FILTRAPAK—Filter press. Diagenex Inc.
FILTREC—Semi-automatic flat-bed pressure filter. Summit Scientific Corp.
FILTRONIC—Automatic filter systems. Summit Scientific Corp.
FINALIZER—Waste treatment equipment. Industrial Filter & Pump Mfg. Co.
FINISH-AID—Rust preventive and drying aid. Pavco Inc.
FINISHMASTER—Vibratory tumbling machines. Bel Air Finishing Supply Inc.
FIRST CHOICE—Autocatalytic palladium plating solution. Callery Chemical Co.
FISHBONE—A titanium anodizing rack. Servi-Sure Corp.
FLAKELINE—Corrosion-resistant epoxy coating. Ceilcote Air Pollution Control
FLAKEPRIME—Epoxy primer. Ceilcote Air Pollution Control
FLAPWHEEL—Abrasive wheel. Schaffner Mfg. Co. Inc.
FLASHVAP—Multistage multi-effect flash evaporator. Licon Inc.
FLEMION—Perfluorinated ion exchange membrane. Asahi Glass America Inc.
FLEX-DRUM—Surface descaling and polishing wheel. Merit Abrasive Products Inc.
FLEX-PLUG—All plastic valve. Vanton Pump & Equipment Corp.
FLEXBAC—Coated abrasives. Carborundum Abrasive Co.
FLEXCORE—Expanding-type polishing wheel. Nu-Matic Grinders Inc.
FLEXICLEAN—Parts washer. Aichelin-Stahl Inc.
FLEXIGRID—Flexible PVC duckboard. Tepromark International Inc.

FLEXLINE—Aqueous cleaning systems. Branson Ultrasonics Corp.
FLEXMAT—Thermoplastic acid-resistant floor tile. McNichols Co.
FLINTFLEX—Epoxy linings. DuPont Co.
FLO-THRU—Vibratory finishing unit. Automated Finishing Inc.
FLOMAG—Magnesia-based chemicals for neutralizing waste streams. Martin Marietta Magnesia Specialties
FLOODJET—Spray nozzle. Spraying Systems Co.
FLOTEC—Pumps for corrosive solutions. Webster Pumps
FLOTREX—Pleated cartridge filters. Osmonics Inc.
FLOW MASTER—Single tank electroless nickel system. Plasfab Inc.
FLUO FREE—Fluoborate-free tin-lead plating process. MacDermid Inc.
FLUOPURE—Fluoborates for general industrial applications. Engelhard Electro Metallics Div.
FLUOREX—Process for regeneration of mixed acids used to pickle stainless steel. Eco-Tec Inc.
FLUORODERM—X-ray fluorescence device for coating thickness measurement. Veeco Industrial Measurement
FLUOROLINE—Lining for electroless nickel tanks. F.C. Witt Associates Ltd.
FLURON—Dry acid salt replacement for hydrofluoric acid solutions. Pax Surface Chemicals Inc.
FLUROPURE—Fluoborates for general metal finishing. Atotech USA Inc.
FOAM BAN—Additive to reduce foam. Pax Surface Chemicals Inc.
FOAM-LOK—Foam blanket for hard chromium plating solutions. Enthone-OMI Inc.
FOGJET—Spray atomizing nozzle. Spraying Systems Co.
FORK LIFT-KARRIER—Device for handling 55-gal drums. Morse Mfg. Co. Inc.
FORMSTONES—Random-shaped resin-bonded tumbling media. Grav-i-Flo Corp.
FORMULA I—Bright nickel plating processes. Atotech USA Inc.
FORTUNE—Preformed tumbling materials. Abrasive Finishing Inc.
FOSBOND—Phosphate coatings. Elf Atochem North America Inc.
FOSCOTE—Iron phosphating process. Pax Surface Chemicals Inc.
FOSRINSE—Neutralizing rinse. Elf Atochem North America Inc.
FRAY-RYTE—Buff of 15 layers of compressed fiber cloth. Munson Machinery Co. Inc.
FREON—Solvent. DuPont Co.
FRIDGEVAP—Heat pump driven evaporator. Licon Inc.
FULLJET—Spray nozzles. Spraying Systems Co.
FUME-LID—Foam-forming fume and mist suppressor for use in anodizing electrolyte, bright dip, and etching solutions. Clariant Corp.
FUMETROL—Fume suppressants. Atotech USA Inc.
FUSION—Plastic plating barrels. Hardwood Line Mfg. Co.
FUTUREMATIC—Automatic programmed hoists. FPI Systems Inc.

G

GALVANO-BLACK—Electrolytic blackening process. Kurts & Wolfe Chemical Co. Inc.
GALVANOTEST—Coulometric thickness gauge. ElektroPhysik U.S.A. Inc.
GARDCO—Paint testing, corrosion control, and laboratory instruments. Paul N. Gardner Co. Inc.
GARDOBOND—Phosphate conversion coatings. Oakite Products Inc., A Member of The Chemetall Group
GARDOCLEAN—Heavy-duty oil-splitting cleaners. Oakite Products Inc., A Member of The Chemetall Group
GATORDECK—Pultruded fiberglass grating. Seasafe Inc.
GATORGRATE—Molded fiberglass grating. Seasafe Inc.
GEMI-NI—Nickel plating brightener. Pavco Inc.
GEMINI—Bright nickel plating process. MacDermid Inc.
GENEDEX—Metal cleaners. Tronex Chemical Corp.
GENESIS—Ultrasonic cleaning system. Crest Ultrasonics Corp.
GENESOLV—Cleaning solvents. AlliedSignal Inc., Fluorine Products
GENKLENE—1,1,1-trichloroethane degreasing solvent. ICI Americas Inc., General Chemicals Dept.
GEO-GUARD—Paint strippers, rust preventives, cleaners, and spray booth products. Calgon Corp.
GEODIMETER—Process control system. Spectra Precision
GEOLAST—Rubber-based lining material. F.C. Witt Associates Ltd.
GILLITE—Low temperature cleaners. PPG Pretreatment & Specialty Products
GILLKLEER—Paint detackifier. PPG Pretreatment & Specialty Products
GLOBALTECH—CFC-free cleaning solvents. JNJ Industries Inc.
GLOBRITE—Cleaners, strippers, and phosphate coatings. Texo Corp.
GOLD BUG—Electrolytic recovery system. Precious Metals Processing Consultants Inc.
GOLD DIGGER—Precious metal recovery system. Jaynor Inc.
GOLD GRABBER—Electrolytic gold recovery system. Cemco International Inc., A Div. of Vanguard Holdings Inc.
GOLD MIZER—Program for total systems approach to plating. Engelhard Electro Metallics Div.
GOLD N WEAR—Gold plating process for jewelry. Advanced Chemical Co.
GOLD-ACE—Precious metal recovery equipment. Technic Inc., Equipment Div.
GOLD-SAVER—Ion exchange process. Technic Inc.
GOLDEN BRASS—Brass plating process. Shipley Ronal
GOLPANOL—Nickel plating brightener. BASF Corp., Chemicals Div.
GOLRIC—Electroless gold plating process. Uyemura International Corp.
GRABBER—Automatic hoist process machine. Walgren Co.
GRANODINE—Zinc phosphate coating for steel and cadmium. Henkel Surface Technologies
GRANOLEUM—Rust preventive. Henkel Surface Technologies
GREASOFF—Biodegradable, water-based cleaning solution. Kleer-Flo Co.
GREEN-LIFE—All cotton bias-type buffs. Schaffner Mfg. Co. Inc.
GRID-COIL—Heat transfer immersion coil. Vulcanium Plating Systems, Div. of Industrial Titanium Corp.
GRIND-O-FLEX—Soft abrasive wheels. Merit Abrasive Products Inc.
GRIPMASTER—Polishing cement. JacksonLea, A Unit of Jason Inc.
GRITITE—Polishing wheel cement. M.P. Iding Co. Inc.
GUARDCOTE—Tank lining material. Advanced Materials Inc.
GUARDIAN—Pump and filter system. SERFILCO Ltd.
GUNJET—Hand-operated spray gun for airless paint spraying. Spraying Systems Co.
GYRA FINISH—Centrifugal force tumbling machine. Grav-i-Flo Corp.
GYRO-PAC—Cleaning and finishing wheel. Norton Co.
GYRO—Degreaser. Detrex Corp., Equipment Div.
GYROMATIC—Centrifugal finishing equipment. Timesavers Inc.

H

HALAR—Drum pumps. Sethco Div., Met-Pro Corp.
HALL COAT—Conversion coatings. Hubbard-Hall Inc.
HALSO—Orthochlorotoluene-based cold degreasing solvent. Occidental Chemical Corp.
HANDYMAN—Portable blast cleaner. Pauli Systems
HARDLUBE—Hard anodizing with a Teflon seal. Sanford Process Corp.
HARPERIZER—Automatic centrifugal finishing equipment. Harper Surface Finishing Systems Inc.
HEATGUARD—Heating control for laboratory Hull cell. McGean-Rohco Inc.
HEEF—High efficiency, etch-free functional chromium plating processes. Atotech USA Inc.
HELI-MASTER—Rotary brushes. Osborn International, A Unit of Jason Inc.
HELITUF—Brush. Osborn International, A Unit of Jason Inc.
HENCO-MASK—Masking material. E/M Engineered Coating Solutions
HERCULES—Sludge filter press. Hoffland Environmental Inc.
HEXMASTER—Dry scrubbing system. Duall Div., Met-Pro Corp.
HI-ALK—Etchant-type aluminum spray cleaner. DuBois, Div. of Diversey Lever
HI-CAP—Polypropylene plating barrels. Jessup Engineering Inc.
HI-STEP—Semibright nickel plating process. Enthone-OMI Inc.
HI-TECHER—Pump for printed circuit board etchants. Vanton Pump & Equipment Corp.
HIPPER-DIPPER—Automatic hopper load transfer on barrel equipment. Singleton Corp.
HON-AN-CUT—Plastic media for tumbling. Ultramatic Equipment Co.
HONEYCOMB—Portable plating barrels. Napco Inc.

HULL CELL—Plating test cell. McGean-Rohco Inc.
HURRICANE—Parts washers. Midbrook Inc.
HURRISAFE—Aqueous cleaners. PCI of America
HUSTLER—Side arm work processor. Walgren Co.
HYD-PRO-CRANE—Hydrostatic programmed hoist. Atotech USA Inc.
HYDRA LIFT-KARRIER—One-man device to move, load, tilt, and drain 55-gal drums. Morse Mfg. Co. Inc.
HYDRA-SHOC—Filters. Industrial Filter & Pump Mfg. Co.
HYDRASONIC—Sonic degreasers and generators. Detrex Corp., Equipment Div.
HYDRO-DEBURR—Deburring process using high pressure water. CAE Cleaning Technologies
HYDRO-ETCH—Stripper for plated plastics. Shipley Ronal
HYDRO-FINISH—Abrading, cleaning, and finishing machines. Pangborn Corp.
HYDRO-PULSE—Modular washing system. Goff Corp., Div. George Fischer Foundry Systems Inc.
HYDROSON—Solvent-free cleaning equipment. Atotech USA Inc.
HYDROSPERSE—Water-wash spray booth compound. OMG Fidelity
HYDRYMAX—Automated sludge dryer. Sperry & Co., D.R.
HYFLEX—Gold plating process. Advanced Chemical Co.
HYPALON—Products based on chlorosulfonated polyethylene. DuPont Co.
HYTECH—Gold plating processes for electronic applications. Advanced Chemical Co.
HYTREX—Polypropylene cartridge filter. Osmonics Inc.

I

I/O DOOR—Plating barrel door opening from inside the barrel. Hardwood Line Mfg. Co.
IDEAL—Tack rags. U.S. Chemical & Plastics Inc.
IDILITE—Aluminum oxide polishing abrasives. M.P. Iding Co. Inc.
IDILON—Coated abrasives. M.P. Iding Co. Inc.
IMMERSO JET—Gas burner. Eclipse Combustion Inc.
IMMERSO-JET—Multistage immersion cleaning process. CAE Cleaning Technologies
IMMERSO-JET—Spray washer. CAE Ultrasonics
IMPERIAL—Buffs. Matchless Metal Polish Co.
IMPULSE—Ion exchange regeneration system. Penfield Liquid Treatment Systems
IMSEAL—Epoxy-type metal sealer. Impco Inc.
IN-FILTRATOR—Simultaneous carbon treating and filtration system. Sethco Div., Met-Pro Corp.
INHIB-ALL—Inhibitors for acid pickling. Plating Resources Inc.
INHIBITEX—Corrosion-inhibiting agents. Atotech USA Inc.
INPRO-CLEAN—Aqueous metal cleaners. Oakite Products Inc., A Member of The Chemetall Group
INPRO-TECT—Nitrite-free cleaners/rust inhibitors. Oakite Products Inc., A Member of The Chemetall Group
INSERTUF—Brush. Osborn International, A Unit of Jason Inc.
INSPECTOR—Dry-film thickness gauge. Elcometer Inc.
INSTA-BLAK—Room temperature blackening solutions. Electrochemical Products Inc. (EPI)
INSTADUCT—Plastic duct and fittings. Fabco Plastics Wholesale Ltd.
INSTAGOLD—Gold plating solutions and systems. Tivian Industries Ltd.
INTELLIGENT—Ampere-hour meter. Technic Inc., Equipment Div.
INTERLOX—Phosphate coatings and cleaners for pretreatment. McGean-Rohco Inc.
INVERGAL—Process for through-hole plating or circuit boards. Dr. Hesse & Cie.
IOCHROME—Vapor deposited chromium. Materials Research Corp.
ION-ALERT—Ion sensing electrode for monitoring copper, silver or cyanide. Kentucky Water Treatment Co. Inc.
IONALYZER—Ion specific analyzer. ATI Orion Research
IONNET—Electrowinning cell. Precious Metals Processing Consultants Inc.
IONOX—Nonflammable alcohol solvents. Kyzen Corp.
IRCO—As a prefix with various endings; conversion coatings, rinses, pickling additives, cleaners. PPG Pretreatment & Specialty Products
IRIDITE—Conversion coatings. MacDermid Inc.
IRILAC—Protective coating, clear finish for metals. MacDermid Inc.
ISO-FLO—Voltage block system for electrostatic waterborne painting. Nordson Corp., Liquid Systems Group
ISOBRITE—Copper, nickel, and zinc plating processes. MacDermid Inc.
ISOPREP—Cleaners and surface preparation materials. MacDermid Inc.
ISOSCOPE—Portable thickness tester. Fischer Technology Inc.
IVADIZER—Process for ion plating of aluminum. Ipsen International Inc.

J

J-BRITE—Additives for tin and tin alloy plating processes. Jaynor Inc.
J-MATE—Continuous sludge dryer. USFilter/JWI
J-PRESS—Liquid/solids filtration and separation device. USFilter/JWI
JAGUAR—Wet abrasive blasting system. Pressure Blast Mfg. Co. Inc.
JENFAB—Continuous-belt conveyor systems. Jensen Fabricating Engineers Inc.
JET FLOW—Laboratory model electroless nickel system. Plasfab Inc.
JET STREAM—External heat exchanger system. E. Braude (London) Ltd.
JET-A-MATIC—Natural gas burner. Proheatco Mfg. Co.
JET—Spray cleaners. McGean-Rohco Inc.
JETAL—Blackening salt. Technic Inc.
JETOIL—Water-soluble oil to coat blackened parts. Technic Inc.
JETVAC—Distillation solvent pump. Finish Thompson Inc.
JEWEL-BRITE—Bright nickel plating process for jewelry. Atotech USA Inc.
JIFFI-LINER—Replacement liner for mass-finishing equipment. USFilter/VL Rampe
JOB'R—Reel-to-reel plating equipment. Carolinch Co.

K

KADIZID—Noncyanide cadmium plating process. Shipley Ronal
KANGAROO—Spring-temper titanium anodizing rack. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
KAPPA ONE—Buffing and polishing robot. Harper Surface Finishing Systems Inc.
KARATCLAD—Bright gold alloy plating process. Enthone-OMI Inc.
KASTONE—Oxidation treatment for cyanide wastes. DuPont Co.
KAT—A palladium-based activator for copper prior to electroless plating. Uyemura International Corp.
KEB—Wire cup brushes. Osborn International, A Unit of Jason Inc.
KEM-O-DRYER—Degreasing solvent and parts drying machines. Detrex Corp., Equipment Div.
KEMBRITE—Brass and copper bright dips. Atotech USA Inc.
KEMFLOC—Flocculating agents. Atotech USA Inc.
KEMGLO—Chemical polishing processes. Atotech USA Inc.
KEMPHOS—Phosphating materials. Atotech USA Inc.
KEMPICKLE—Pickling materials. Atotech USA Inc.
KEMSOLV—Mild soak cleaner. Atotech USA Inc.
KEMSPRAY—Spray cleaners. Atotech USA Inc.
KEMSTRIP—Cyanide-free electrolytic process for stripping bright nickel from steel. Atotech USA Inc.
KEMTEX—Alkaline cleaning processes. Atotech USA Inc.
KENLEVEL—Chloride zinc plating process. MacDermid Inc.
KENVERT—Conversion coatings. MacDermid Inc.
KEPHOS—Phosphate coating. Henkel Surface Technologies
KEYKOTE—Phosphating compound. MacDermid Inc.
KING CATHODE—Danglers for barrel plating. Imperial Industries Inc.
KLAIRIFIANT—Water-wash compound for spray booth water curtains. DuBois, Div. of Diversey Lever
KLEER AID—Pollution control products. McGean-Rohco Inc.
KLEM KOTE—Phosphate coating process. Stan Sax Corp.
KLEM STRIP—Paint remover. Stan Sax Corp.
KOLOR-N-KOTE—Water-reducible paints. McGean-Rohco Inc.
KON-DEN-SOLVER—Solvent vapor recovery systems. United Air Specialists Inc.
KONTINUOUS—Molten salt stripping system. Kolene Corp.
KONTROL-KARRIER—Remote control unit for handling drums. Morse Mfg. Co. Inc.
KOOL BOND—Nonphosphate pretreatment coating. PPG Pretreatment & Specialty Products
KORDEK—Plastic floor grating. Atlas Minerals & Chemicals Inc.

KORO AID—Rust inhibiting post dip for phosphating. Haviland Products Co.
KOROSEAL—Flexible and rigid molded and extruded plastic products. BFGoodrich Co., Corzan Industrial Systems Div.
KUPRALUME—Copper plating process. Alchem Corp.
KWIKY DOT—Masking disks. Shercon Inc.
KYNAR—Polyvinylidene fluoride thermoplastics. Elf Atochem North America Inc.

L

LABLOCK—Sputter coater. Vacuum Inc.
LABMASTER—Pump and filter system. SERFILCO Ltd.
LAMELLA—Inclined-plate gravity separation equipment. Parkson Corp.
LANCY—Sorption filter system for waste treatment. USFilter/Warrendale
LARGO—Tanks, linings, and fume scrubbers. Goad Co.
LASERPERF—Plating barrel with laser-drilled holes. Hardwood Line Mfg. Co.
LAZO—Lucite plating barrels. Hardwood Line Mfg. Co.
LAZY PUP—Deep bed filter. Industrial Filters Co.
LEABRAMENT—Polishing cement. JacksonLea, A Unit of Jason Inc.
LEABRITE—Room temperature anodizing sealant, chemical polishes, and plating processes. JacksonLea, A Unit of Jason Inc.
LEAROK—No-free-grease buffing composition. JacksonLea, A Unit of Jason Inc.
LEATARDENT—Water-staining preventive for plated work. JacksonLea, A Unit of Jason Inc.
LECTRA + COTE—Electropainting system. Cincinnati Industrial Machinery, Div. of Eagle Picher Industries Inc.
LECTRO-CLAIM—Precious metal recovery system. Cemco International Inc., A Div. of Vanguard Holdings Inc.
LECTRO-NIC—Nickel plating process. Enthone-OMI Inc.
LECTROLESS NI—Electroless nickel plating process. Enthone-OMI Inc.
LECTROLESS-AU—Electroless gold plating processes. Enthone-OMI Inc.
LECTROMIZER—Submerged bus bar. SPF Corp. of America
LENIUM—Solvent for use with vapor degreasers. Petroferm Inc.
LEVEL-MATIC—Automatic control for a corrosion test cabinet. Singleton Corp.
LEVELBRITE—Bright nickel plating process. MacDermid Inc.
LEVELUME—Bright nickel plating process. Atotech USA Inc.
LEWATIT—Ion exchange resins. Bayer Corp., Industrial Chemicals Div.
LI'L GUY—Compact horizontal plate filter. Anode Products Co. Inc.
LIBERTY COAT—Porcelain enamel frit. Ferro Corp., Powder Coatings Div.
LIFTKLEEN—Automatic parts cleaner. Graymills Corp.
LINEGUARD—Automatic process control system. Henkel Surface Technologies
LIONBLAST—Blasting and cleaning aluminum oxide. Treibacher Schleifmittel Corp.
LIONITE—Aluminum oxide abrasive. Treibacher Schleifmittel Corp.
LIQUA-SHEEN—Liquid burnishing compound. JacksonLea, A Unit of Jason Inc.
LIQUABRADE—Continuous spray buffing system. JacksonLea, A Unit of Jason Inc.
LIQUALUBE—Water-soluble liquid lubricant for polishing wheels and belts. JacksonLea, A Unit of Jason Inc.
LIQUI-NOX—Detergent. Alconox Inc.
LIQUIBUFF—Liquid buffing compound. M.P. Iding Co. Inc.
LIQUID HONING—Wet blasting system. Vapor Blast Mfg. Co.
LIQUIFUGE—Centrifugal oil separator. Barrett Centrifugals Inc.
LIQUIMATIC—Liquid buffing compounds. JacksonLea, A Unit of Jason Inc.
LIQUIPRO—Metering pumps. LMI, Div. of Milton Roy
LIQUITRON—pH and ORP controllers. LMI, Div. of Milton Roy
LIVELLO—Bright nickel plating process. Bison Corp.
LO-MIST—Fume suppressant for anodizing and chromium plating baths. Accurate Engineering Labs, Div. of Rin Inc.
LOAD LOCKER—Plating barrels. Jessup Engineering Inc.
LOMAT—Conversion coating for zinc. Okuno Chemical Industries Co. Ltd.
LONG-LYFE—Cast replacement parts for abrasive blasting equipment. USFilter/Wheelabrator
LONOX—VOC sensitive cleaning process. Kyzen Corp.
LOW BOY—Plating barrel support structure. Singleton Corp.
LUBAR—Polishing wheel lubricant. JacksonLea, A Unit of Jason Inc.
LUBE-LOK—Oven-cured solid film lubricant. E/M Engineered Coating Solutions
LUBRI-BOND—Air-drying solid film lubricant. E/M Engineered Coating Solutions
LUCINA—Bright acid and high-speed copper brighteners. Okuno Chemical Industries Co. Ltd.
LUCITE—Acrylic lacquer, mixing and tinting colors, topcoat sealer. DuPont Co.
LUMA-CHROME—Self-regulated microcracked chromium plating process. Atotech USA Inc.
LUNACID—Bright zinc plating process. Dr. Hesse & Cie.
LUSTER-FOS—Phosphate coating. Luster-On Products Inc.
LUSTER-LAC—Water-based clear lacquer. Luster-On Products Inc.
LUSTERCAST—Zinc diecast soak cleaner. Haviland Products Co.
LUSTRA—Zinc and cadmium plating processes and additives. Heatbath Corp.
LUSTRALITE—Bronze plating process. Enequist Chemical Co. Inc.
LUXAMATIC—Greaseless compound for liquid satin finishing. JacksonLea, A Unit of Jason Inc.

M

MACRO BRITE—Chromate conversion coatings. MacDermid Inc.
MACROLOY—Chromate conversion coatings for zinc alloys. MacDermid Inc.
MACROMATE—Conversion coatings. MacDermid Inc.
MACROME—Chromium plating processes. MacDermid Inc.
MACUGUARD—Mechanical galvanizing process. MacDermid Inc.
MACUPLEX—Process for plating on plastics. MacDermid Inc.
MACUSHIELD—Process for EMI shielding. MacDermid Inc.
MAGALLOY—Mass-finishing compounds for stainless steels. REM Chemicals Inc.
MAGENTA—Process for plating electroless nickel on magnesium alloys. Atotech USA Inc.
MAGNA LIF—Air-powered parts washer. PPG Pretreatment & Specialty Products
MAGNA VALVE—Control valve for abrasive blasting with steel shot. Electronics Inc.
MAGNAPAK—Ultrasonic transducers. Rosemont Analytical
MAGNATRAK—Ultrasonic generators. Rosemont Analytical
MAGNUM—Bright nickel plating process. Enthone-OMI Inc.
MAGNUS—Agitation cleaning and processing equipment. PPG Pretreatment & Specialty Products
MAGPRIME—Magnetic-drive, self-priming centrifugal pumps. Finish Thompson Inc.
MAKERCLEAN—Aqueous cleaners and descalers. Chemtech Finishing Systems Inc.
MAKROLUX—Bright nickel plating process. Atotech USA Inc.
MAPCO—Fans, hoods, and fume scrubbers. Midwest Air Products Co. Inc.
MARATHON—Vertical immersible sealless pump. Webster Pumps
MARK 90—Semibright nickel plating process. Atotech USA Inc.
MASTER-MATIC—Automatic plating equipment. Upton Industries Inc.
MASTER—Spiral brushes. Osborn International, A Unit of Jason Inc.
MASTERBLAST—Abrasive media for blasting. Norton Co.
MASTERFLEX—Peristaltic tubing pumps. Barnant Co.
MATIC—Short-trim wire wheel brushes. Osborn International, A Unit of Jason Inc.
MAX-EVAP—Evaporator for metal recovery. Palm Commodities International Inc.
MAX-PAC—Shell-and-tube heat exchanger. AstroCosmos Metallurgical Inc.
MAXAMP—Electrocleaning processes. Chemtech Finishing Systems Inc.
MAXBRITE—Nickel plating brightener and leveling agent. Pax Surface Chemicals Inc.
MAXHESIVE—Corrosion-resistant cement. Ceilcote Air Pollution Control

MAXI-FILTER—Filter for chloride zinc baths. Palm Commodities International Inc.

MAXI-POLISH—Effluent polishing filter. Palm Commodities International Inc.

MAXI—Plating barrels. Singleton Corp.

MEBCO—Tank rheostat, rod agitation, selenium rectifier, and plating console. M.E. Baker Co.

MEC-O-MATIC—Metering pump. Pulsafeeder Inc., A Unit of Idex Corp.

MEGALLOY—Chemically-accelerated mass-finishing compounds for stainless steels. REM Chemicals Inc.

MELLAFIER—Inclined plate clarifier. Industrial Filter & Pump Mfg. Co.

MELONITE—Liquid nitrocarburizing process. Houghton International Inc.

MEMBRALOX—Cleaner recovery system. USFilter/Warrendale

MEMODERM—Microcomputer thickness measurement device. Veeco Industrial Measurement

MEMTREX—Cartridge filters. Osmonics Inc.

ME[illegible]IL—Plating barrels, tanks, and dryers. Napco Inc.

ME[illegible]—Bright nickel plating process. Plating Process Systems Inc.

ME[illegible]UR—Brass plating process. Dr. Hesse & Cie.

ME[illegible]MAID—Pump and filter system. SERFILCO Ltd.

ME[illegible]—Coated abrasive belts. Munson Machinery Co. Inc.

ME[illegible]RONIC—Metal recovery equipment. RRC Agmet Inc.

META-BLACK—Blackening processes for copper, steel, and zinc. Metal Chem Inc.

META-BOND—Microcrystalline zinc phosphate coating. PPG Pretreatment & Specialty Products

META-BRITE—Bright dipping products. Metal Chem Inc.

META-CID—Acid cleaners. Metal Chem Inc.

META-GLEEM—Burnishing products. Metal Chem Inc.

META-HIB—Rust and tarnish preventives. Metal Chem Inc.

META-KLEEN—Alkaline cleaners. Metal Chem Inc.

META-LAC—Lacquer sealants. Metal Chem Inc.

META-MATE—Activators and oxide removal products. Metal Chem Inc.

META-PHOS—Iron and zinc phosphate coating processes. Metal Chem Inc.

META-PLATE—Electroless, electrolytic, and immersion plating processes. Metal Chem Inc.

META-STRIP—Metal and paint strippers. Metal Chem Inc.

META-TREAT—Waste treatment chemicals. Metal Chem Inc.

META-WET—Surfactants. Metal Chem Inc.

METAC—Recycling system to reclaim acid and metals from ion exchange columns. Larry King Corp.

METALEX—Cleaners. MacDermid Inc.

METALGUARD—Water-displacing rust preventive for ferrous parts. Hubbard-Hall Inc.

METALITE—Abrasive belts. Norton Co.

METALLOY—Metallic filler. U.S. Chemical & Plastics Inc.

METALNOX—Precision metal cleaning process. Kyzen Corp.

METEX—Metal finishing compounds and cleaners. MacDermid Inc.

MICCRO—Prefix with various endings; stop-off lacquers, air-dry rack coatings, insulating & masking tape, lacquer & plastisols. Tolber Div., Pyramid Plastics Inc.

MICRO SEP—Filtration system. R-V Industries Inc.

MICRO-DERM—Nondestructive beta backscatter plating thickness gauge. Veeco Industrial Measurement

MICRO-MESH—Abrasive belts. Micro-Surface Finishing Products Inc.

MICRO-MINI—Abrasive flap wheel. Merit Abrasive Products Inc.

MICRO-PHASE—Micro-emulsion metal cleaner. PPG Industries Inc.

MICRO-POLISHER—Polishing machine. Acme Mfg. Co.

MICRO-PORE—Sealing process for castings. Impco Inc.

MICROBARREL—Very small plating barrel. Belke Mfg. Co.

MICROCROWNS—Electrolytic nickel anodes. Falconbridge U.S. Inc.

MICRODIP—Microporous chromium dip over nickel. Atotech USA Inc.

MICROETCH—Etch processes for printed circuit boards. Engelhard Electro Metallics Div.

MICROFAB—Semiconductor-grade plating processes. Enthone-OMI Inc.

MICROGOLD—Electroless gold plating system. Stapleton Technologies

MICROJET—Abrasive blasting equipment. Hunter Products Inc.

MICROLOK—Zinc phosphate solution for iron and steel. Birchwood Laboratories Inc.

MICROMESH—Titanium anode baskets. AstroCosmos Metallurgical Inc.

MICROPAK—Pulse-plating power supply. PWR Inc.

MICROPUR—Ion exchange system for pickling and etching. Eco-Tec Inc.

MICROPURE—Circuit board cleaner. International Specialty Products

MICROSTAR—Pulse-plating power supply. PWR Inc.

MIGHTY-BRITE—Chemical feeder. Mesa West Inc.

MIGHTY-MATIC—Bridge-crane-type plating hoist. Upton Industries Inc.

MIGI-KLEEN—Hot air dryers. Ramco Equipment Corp.

MIJI-LIF—Small parts washer. PPG Pretreatment & Specialty Products

MIKROTEST—Dry-film thickness gauge. ElektroPhysik U.S.A. Inc.

MILLENIUM—Acid zinc plating process. Dr. Ing. Max Schlötter

MILLENIUM—Electroless nickel plating processes. Sirius Technology Inc.

MINERALMIZER—Vacuum recovery system. SPF Corp. of America

MINI-BELL—Electrostatic painting equipment. ITW Ransburg Electrostatic Systems

MINI-BOBS—Small abrasive impregnated fabric wheel. Even Cut Abrasive Co.

MINI-SUBX—Small sized submerged filter system. Sethco Div., Met-Pro Corp.

MINIDERM—Hand-held, battery-operated thickness gauge. Veeco Industrial Measurement

MINIPREP—Table-top plating line for Hull cell. Larry King Corp.

MINISPOT—Reel-to-reel selective plating equipment. Meco Equipment U.S.A. Inc.

MINITEST—Portable coating thickness gauge. ElektroPhysik U.S.A. Inc.

MIRA-CAD—Noncyanide cadmium plating process. Chemtech Products Inc.

MIRROMAC—Bright cyanide zinc plating process. MacDermid Inc.

MIST BAN—Fume suppressant for anodizing, chromium plating, and copper baths. Pax Surface Chemicals Inc.

MIST CONTROL—Fume suppressant for chromium plating baths. Belke Mfg. Co.

MISTKOP—Mist collectors. Aget Mfg. Co.

MITY-MITE—Cover lifting system for plating barrels. Singleton Corp.

MOBILE KARRIER—Drum handling truck. Morse Mfg. Co. Inc.

MOCO—Polishing, buffing, and barrel finishing compounds. Mosher Co. Inc.

MODUFLEX—Contour finishing machine. Munson Machinery Co. Inc.

MODULE-MASQ—Automated plating equipment. Enthone-OMI Inc.

MODULE-MATIC—Programmed automatic plating equipment. Enthone-OMI Inc.

MODULE-X—Modular plating system. Enthone-OMI Inc.

MOGUL—Reel-to-reel plating system. Carolinch Co.

MOLYKOTE—Solid film lubricants. Dow Corning Corp.

MONARCH—Tampico brushes. Osborn International, A Unit of Jason Inc.

MONITOR—Wire wheel brushes. Osborn International, A Unit of Jason Inc.

MORPHOS—Iron phosphate compounds. Heatbath Corp.

MPS-100—Microcracking nickel. Atotech USA Inc.

MULTI-BLAST—Granulated urea blasting media. Maxi-Blast Inc.

MULTI-BRADE—Mass-finishing media. C&S Engineering Corp.

MULTI-HONE—Media for mass finishing composed of quartz abrasive in polyester resin. C&S Engineering Corp.

MULTI-MAG CATHODES—Sputter deposition source. Vacuum Inc.

MULTI-PASS—Continuous vibratory finishing system. Roto-Finish Co. Inc.

MULTI-ZONE—Heat exchanger. Tranter Inc.

MULTICELL—Plating test cell. Larry King Corp.

MULTICLAMP—Anodizing clamp. Moldsaver Inc.

MULTIPREP—Plating pretreatment process. MacDermid Inc.

MULTITRON—Preparation treatments for circuit boards. Atotech USA Inc.

MY T KLEEN—Line of ferrous metal soak cleaners. A Brite Co.

N

NALMET—Precipitating agent for heavy metals. Nalco Chemical Co.
NAPVAP—Atmospheric evaporator. Napco Inc.
NARACO—Plating racks, anodizing racks, and plastisol insulation. National Rack Co.
NATCO—Steam boilers. National Combustion Co. Inc.
NAUTILUS—Heating and cooling equipment. E. Braude (London) Ltd.
NEO-STAR—Bright zinc plating process. Atotech USA Inc.
NEOCHEL—Additive for cyanide copper and bronze plating processes. Atotech USA Inc.
NEOCOAT—Corrosion-resistant coatings and cements. Elf Atochem North America Inc.
NEOLINE—Corrosion-resistant coatings and cements. Elf Atochem North America Inc.
NEORUM—Neutral electroless gold plating process. Uyemura International Corp.
NEUTRA CLEAN—Mild soak cleaner for copper and copper alloys. Shipley Ronal
NEUTRONEX—Neutral noncyanide plating process. Enthone-OMI Inc.
NEVER DUMP—Aluminum acid cleaner, etch process, desmutter, and deoxidizer. Haviland Products Co.
NEW DIMENSIONS—Cleaners. MacDermid Inc.
NI-ALLOY—Zinc-nickel electroplating process. Deveco Corp.
NI-CORR—Electroless nickel bath for high corrosion resistance. Surface Technology Inc.
NIACT—Nickel activator prior to chromium plate. Plating Process Systems Inc.
NIAGARA BLAST—Aluminum oxide blasting media. Washington Mills Electro Minerals Corp.
NIAPROOF—Anionic surfactants suitable for acid and caustic solutions. Niacet Corp.
NICHEM—Electroless nickel plating process. Atotech USA Inc.
NICKEL PLUS—Bright nickel plating processes. A Brite Co.
NICKEL SHIELD—Bright nickel plating process. A Brite Co.
NICKEL SOL—Stripper for nickel and copper. Electrochemicals
NICKEL STORM—Bright nickel plating process. A Brite Co.
NICKEL-GLEAM—Bright nickel plating process. Shipley Ronal
NICKEL-LUME—Bright nickel plating process. Atotech USA Inc.
NICKEL-X—Ammonia-free electroless nickel plating solution. Transene Co. Inc.
NICKELDERM—Nondestructive nickel thickness measuring instrument. Veeco Industrial Measurement
NICKELIN—Nickel-phosphorus alloy plating bath. Okuno Chemical Industries Co. Ltd.
NICKELSCOPE—Thickness testing instrument for nickel. Fischer Technology Inc.
NICLEAN—Mild acid cleaner for aluminum. Atotech USA Inc.
NICONIUM—Bright nickel plating process for zinc diecastings. Shipley Ronal
NICORON—Electroless nickel polyalloy plating processes. Okuno Chemical Industries Co. Ltd.
NICROLYTE—Process for plating nickel and chromium on stainless steel. Enthone-OMI Inc.
NICULOY—Electroless nickel-copper-phosphorus alloy coating. Shipley Ronal
NIFERLOY—Nickel-iron plating process. Plating Process Systems Inc.
NIFLOR—Nickel-PTFE composite plating process. Atotech USA Inc.
NIFLOW—Semibright nickel plating process. MacDermid Inc.
NIKAL—Bright nickel process for printed circuits. Shipley Ronal
NIKE—Nickel brightener. Plating Products Co. Inc.
NIKLAD—Process for plating on plastics and printed circuits. MacDermid Inc.
NIKLPURE—Nickel plating purification equipment. Summit Scientific Corp.
NIKORA—Electroless nickel plating process. Atotech USA Inc.
NIMAC—Nickel plating processes. MacDermid Inc.
NIMUDEN—Electroless nickel plating process. Uyemura International Corp.
NIPLEX—Nickel stripping process. Atotech USA Inc.
NIPOSIT—Electroless nickel plating processes including strippers for same. Shipley Ronal
NIPROTEQ—Bright nickel plating process. Atotech USA Inc.
NIRON—Nickel-iron plating process. Enthone-OMI Inc.
NISAT—Satin nickel plating process. Plating Process Systems Inc.
NISTAN—Tin-nickel alloy plating process. Atotech USA Inc.
NISTRIP—Nickel stripper. Surface Technology Inc.
NITEC—Electroless nickel plating processes. Heatbath Corp.
NO BAKE CADMIUM—Selective cadmium plating process. Sifco Selective Plating, Div. of Sifco Industries Inc.
NO-NUBBIN—Nubless buffing compositions. Schaffner Mfg. Co. Inc.
NO-SPILL—Drum cart. Morse Mfg. Co. Inc.
NOBLECOAT—Insoluble anodes for plating gold and platinum on other metals. Engelhard Electro Metallics Div.
NOCHROME—Wet scrubber system for hexavalent chromium. Tri-Mer Corp.
NON-FRAY—Buffs. F.L. & J.C. Codman Co.
NON-STREAK—Polishing wheels. Munson Machinery Co. Inc.
NORBIDE—Abrasives and nozzles for pressure and sand blasting. Norton Co.
NORTHWEST—Cleaners, burnishing compounds, strippers, polishing processes, bright dips, and aluminum processing compounds. McGean-Rohco Inc.
NORZON—Coated abrasives. Norton Co.
NOVA—Bright nickel plating process. Atotech USA Inc.
NOVABAT—Bright acid tin plating processes. Chemtech Finishing Systems Inc.
NOVACHLOR—Acid chloride zinc and zinc alloy plating processes. Aldoa Co.
NOVACITE—Novaculitic tripoli or altered novaculite. Malvern Minerals Co.
NOVADIP—Topcoats for zinc plate. Chemtech Finishing Systems Inc.
NOVAKAP—Treated quartz microform abrasives. Malvern Minerals Co.
NOVALYTE—Cadmium and zinc plating processes. Aldoa Co.
NOVASTAN—Immersion tin plating processes. Chemtech Finishing Systems Inc.
NOVATECT—Electroless nickel plating process. Atotech USA Inc.
NOVATRONIX—Nickel sulfate plating processes. Atotech USA Inc.
NOVIGANTH/PRINTOGANTH—Electroless copper bath for circuit boards. Atotech USA Inc.
NU-TRIDE—Salt nitriding process to produce black corrosion-resistant finish. Kolene Corp.
NUMATIC—Automatic multistage cleaning machine. PPG Pretreatment & Specialty Products
NUSAT—Satin finish nickel plating process. Atotech USA Inc.
NUVAT—Aqueous soak cleaners. Chemtech Finishing Systems Inc.
NYBRAD—Nylon monofilament abrasive. Glassmaster Monofilament Div.
NYLOX—Abrasive-filled nylon power brushes. Weiler Corp.

O

OKEMCOAT—Conversion coating for zinc. Oakite Products Inc., A Member of The Chemetall Group
OMEGA SUPER—Semibright nickel plating process. Dr. Hesse & Cie.
OMEGA—Electroless nickel plating system. Stapleton Technologies
OMNI-FOG—Dispersion system for salt fog test chambers. Atlas Electric Devices Co.
OMNIPAC—Column for high performance liquid chromatography. Dionex Corp.
OMNISHIELD—Processes for plating on plastics. Shipley Ronal
ON-BOARD—Cryogenic vacuum pump. CTI-Cryogenics Div., Helix Technology Corp.
ON-LINE—Electroplating thickness monitor. Maxtek Inc.
OPTI-FOG—Corrosion test cabinets. Singleton Corp.
OPTIMA—Clad insoluble anodes. Electrode Products Inc.
OPTIMUM—Ultrasonic cleaning system. Crest Ultrasonics Corp.
ORANGE BOWL—Vibratory finishing machine. Almco Inc.
ORASORB—Carbon filter cartridge. Enthone-OMI Inc.
ORION—Bright nickel plating process. JacksonLea, A Unit of Jason Inc.
ORO—As a prefix with various endings, gold plating solutions, chemicals, and supplies. Technic Inc.
OSCILINE—Vibratory plating process. ECI Technology Inc.
OSCILLANT—Vibratory plating baskets. ECI Technology Inc.
OTTO-MATIC—Programmed etchback and rinsing system. M.E. Baker Co.
OWEN—Selective plating equipment. International Surface Technology Ltd.
OXICOAT—Immersion treatment for chromium and stainless steel alloys. Heatbath Corp.

OXSOL—Solvents. Occidental Chemical Corp.
OXY-FREE—Silver anodes. Reliable-West Tech Inc.
OXYCAT—Air pollution control devices. Met-Pro Corp., Systems Div.

P

PACKERMATIC—Automatic buffing equipment. Harper Surface Finishing Systems Inc.
PADDLE WHEEL—Modular plating barrel. Hardwood Line Mfg. Co.
PAINTKILL—Spray booth cleaning compound. Calgon Corp.
PALLABAR—Bright, neutral palladium plating solution. Technic Inc.
PALLADEX—Low-stress palladium plating process. Enthone-OMI Inc.
PALLADO-BRUSH—Palladium brush plating gel. Technic Inc.
PALLADURE—Palladium plating process. Shipley Ronal
PALLAMERSE—Immersion palladium plating process. Technic Inc.
PALLAMET—Palladium-nickel plating process. Shipley Ronal
PALLASIL—Palladium-silver plating process. Shipley Ronal
PALLASPEED—High-speed bright palladium plating process. Technic Inc.
PALLATECH—Palladium and palladium alloy plating processes. Lucent Technologies
PALLNIC—Palladium-nickel alloy plating process. Engelhard Electro Metallics Div.
PALLTRONIC—Palladium plating process. Engelhard Electro Metallics Div.
PANTHER BLACK—Black oxide coatings. McGean-Rohco Inc.
PARAGON—Cleaning compound. Pavco Inc.
PARCOLENE—Chromium-free post treatment. Henkel Surface Technologies
PARKERIZING—Phosphate coatings. Henkel Surface Technologies
PARTSPREP—Degreasing solvent. International Specialty Products
PASER—Water-jet abrasive blasting equipment. Flow Systems Inc.
PATCOALUM—Dyes for anodized aluminum. C.H. Patrick & Co. Inc.
PATINAL—Evaporation materials for vacuum deposition. EM Industries Inc.
PAUL FRANK—pH test papers. Fil-Chem Inc., Paul Frank Div.
PAVCHROME—Olive drab conversion coating for zinc and cadmium. Pavco Inc.
PEELCOTE—Temporary barrier coating for paint spray booths. ACI Chemicals Inc.
PEN DIP—Rust-preventive water-displacing oil. Heatbath Corp.
PENCHLOR—Acid-proof cement. Elf Atochem North America Inc.
PENGUIN—Pumps, filters, precious metal recovery equipment, tanks, and mixers. Filter Pump Industries, Div. of Penguin Pumps Inc.
PENNGUARD—Acid-proof cement. Elf Atochem North America Inc.
PENNTROWEL—Floor surfacing compound. Elf Atochem North America Inc.
PENTADRUM—Mass-finishing tumbling equipment for blackening. Du-Lite Corp.
PENTEST—Small-size thickness gauge. ElektroPhysik U.S.A. Inc.
PENTRATE ULTRA—Black oxide coatings on steel. Heatbath Corp.
PEP—Porcelain enamel powder. O. Hommel Co.
PEPTIZOID—Cleaning, surface treatment, burnishing, and deburring compounds. MacDermid Inc.
PERC—Inorganic powder coatings (porcelain enamel). Ferro Corp., Powder Coatings Div.
PERCLENE—Perchloroethylene vapor degreasing solvent. Metal Coatings International Inc.
PERFLOW—Nickel plating process. Atotech USA Inc.
PERJ—Compound for cleaning paint spray booths. DuBois, Div. of Diversey Lever
PERM A CHLOR—Cleaning solvents. Detrex Corp., Solvents and Environmental Services Div.
PERM-AU-TONE—Gold plating processes for jewelry. Advanced Chemical Co.
PERM-O-FLOTE—Polypropylene floating balls. Savitt Industrial Products Inc.
PERMA PASS—Chemical passivating agent. Enthone-OMI Inc.
PERMA-DISC—Horizontal cartridge filter disk. Contaminant Recovery Systems Inc.
PERMA-FLEX—Titanium anodizing racks with spring-action fingers. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
PERMA-GRIP—Bonding process for joining fiberglass to other materials in fume scrubbing equipment. Duall Div., Met-Pro Corp.
PERMA-KOTE—Filter sleeve elements. Summit Scientific Corp.
PERMA—As a prefix with various endings, bright cyanide copper bath, bright zinc process, and bright cyanide cadmium bath. Starlite Technical Service Inc.
PERMACORE—Reusable filter cartridges. Flo King Filter Systems Custom Masters Inc.
PERMAG—Metal cleaners. Magnuson Product Corp.
PERMALUME—Semibright nickel plating process. Atotech USA Inc.
PERMANODE—Platinized tantalum anode. Enthone-OMI Inc.
PERMAPOWER—Trichloroethylene and perchloroethylene for vapor degreasing. Occidental Chemical Corp.
PERMASCOPE—Thickness tester for coatings on ferrous metals and for anodic coatings. Fischer Technology Inc.
PERMASEP—Reverse osmosis modules. DuPont Co.
PERMASLIK—Solid film lubricant. E/M Engineered Coating Solutions
PERMATREAT—Conversion coatings and passivation treatments. BetzDearborn, Div. of Hercules Inc.
PERSTRIP—Plastic media for dry stripping. Composition Materials Co. Inc.
PETE—Portable ion exchange unit to recover low concentrations of heavy metals. Bio-Recovery Systems Inc.
PHASE-O-MATIC—Plating rectifiers. Clinton Power, Subsidiary of Benjamin Power Co.
PHOS BLACK—Prephosphate color-conditioning agent. Deveco Corp.
PHOS GREEN—Post-phosphate water-based dye. Deveco Corp.
PHOS-DIP—Phosphate coatings. Heatbath Corp.
PHOSBRITE—Bright dips for aluminum. Albright & Wilson Americas
PHOSEAL—Phosphate seal. Heatbath Corp.
PHOSGARD—Nonchrome phosphate sealer. BetzDearborn, Div. of Hercules Inc.
PHOSGUARD—Phosphate coatings. Tronex Chemical Corp.
PHOSHIELD—Iron, zinc, and manganese phosphating processes. A Brite Co.
PHOSPHOTEX—Zinc phosphating process. MacDermid Inc.
PICKLE PAL—Inhibitor for hydrochloric and sulfuric acid pickling baths. Columbia Chemical Corp.
PICKLEEN—Ferrous metal acid additives. A Brite Co.
PICKLIQ—Process for recycling acids. Green Technology Group
PICTAX—Dry acid salts and acid additives. Chemtech Finishing Systems Inc.
PIONEER—Polishing wheels. Matchless Metal Polish Co.
PITCHBLACK—Blackening products for ferrous and nonferrous metals. A Brite Co.
PITSTOP—Sacrificial magnesium anode to prevent pitting in anodizing. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
PLASTALON—Plating-on-plastic processes. Engelhard Electro Metallics Div.
PLASTI-GRIT—Plastic media for dry stripping. Composition Materials Co. Inc.
PLASTI-KLENZ—Plastic cleaners. Calgon Corp.
PLASTIBRADE—Polishing cement. JacksonLea, A Unit of Jason Inc.
PLASTICLAD—Greaseless compound for satin finishing. JacksonLea, A Unit of Jason Inc.
PLASTICRESIN—Polishing cement. JacksonLea, A Unit of Jason Inc.
PLASTSHINE—Buffing compound for plastics. JacksonLea, A Unit of Jason Inc.
PLATANEX—Platinum plating process. Enthone-OMI Inc.
PLATANIUM—Insoluble anodes. Enthone-OMI Inc.
PLATECOIL—Heat exchanger. Tranter Inc.
PLATIMINN—Bright acid tin-zinc plating process. Chemtech Products Inc.
PLATINO-BRUSH—Platinum brush plating gel. Technic Inc.
PLATIQUE—Blackening process for ferrous and nonferrous metals. Plating Products Co. Inc.

PLATTZINK—Zinc-aluminum metallizing wire. Platt Bros. & Co.
PLUS-PLUGS—Vinyl stop-off plugs. StockCap, A Sinclair & Rush Co.
PLUTIN—Tin-lead plating process. Shipley Ronal
POLARIS—Bright cyanide copper plating process. Atotech USA Inc.
POLY FLEX—Encapsulated brushes. Weiler Corp.
POLY SPRAY—Cleaners for plastic. PPG Pretreatment & Specialty Products
POLY-FINE—Pleated polypropylene filter cartridge. *USFilter/Filterite*
POLY-HONE—Plastic media for mass finishing. Automated Finishing Inc.
POLY-RIPPLE—Plating barrel surface interior. Singleton Corp.
POLYALL—Wastewater treatment additive. A Brite Co.
POLYBALLS—Plastic fume suppressants. Southwest United Industries Inc.
POLYCERAGUARD—Spraybooth coating for grates. BetzDearborn, Div. of Hercules Inc.
POLYFILM—Rust and corrosion inhibitors. Tronex Chemical Corp.
POLYFLOC—Wastewater treatment additive. A Brite Co.
POLYLOC—Snap-fit collar for filter bags. Filter Specialists Inc.
POLYMASTER—Automatic blending feeder. Komax Systems Inc.
POLYSEAL—Corrosion-resistant finish system. PPG Pretreatment & Specialty Products
POLYSEP—Cartridge for ultrafiltration in electropainting. UFS Corp.
POLYSTRIP—Stripping agents. Plating Resources Inc.
POLYWELD—Filter bag. Filter Specialists Inc.
POLYZINC—Organic zinc-rich coating. Ceilcote Air Pollution Control
POPCORN—Silver anodes. Reliable-West Tech Inc.
POROPRINT—Porosity measuring device. Fischer Technology Inc.
POROSCOPE—High voltage porosity tester. Fischer Technology Inc.
POROTEST—Thickness testing equipment. ElektroPhysik U.S.A. Inc.
PORTA BLASTER—Small portable vacuum blasting cabinet. Liquid Development Co.
PORTABURR—Vibratory finishing machine. Ultramatic Equipment Co.
PORTAPAK—Electrostatic power supply unit. ITW Ransburg Electrostatic Systems
PORTO-PLATER—Portable small-lot plating barrel with self-contained motor drive. Belke Mfg. Co.
POSI-FILTER—Pressurized bailer system for on-site collection of filtered samples. Norton Performance Plastics Corp.
POSIPEN—Thickness gauge for nonmagnetic coatings on steel. DeFelsko Corp.
POSITECTOR—Pocket-sized digital coating thickness gauge. DeFelsko Corp.
POSITEST—Thickness tester for nonmagnetic coatings on steel. DeFelsko Corp.
POWDERGRID—Cartridge filter for powder coating spray booths. Nordson Corp., Liquid Systems Group
POWER KLEEN—Electropolishing process. Molectrics Inc.
POWER-LOCK—Mechanical lock abrasive sanding disk. Merit Abrasive Products Inc.
POWER-MATIC—Automatic load/unload door operation on barrel-type equipment. Singleton Corp.
POWER-PRIME—Primer for electrocoating. PPG Industries Inc.
POWER-TERG—Spray metal cleaners. Tronex Chemical Corp.
POWERCRON—Electrocoatings. PPG Industries Inc.
POWERMASTER—Parts washer. Kleer-Flo Co.
POWERMATIC—Pump for corrosive chemicals. Pulsafeeder Inc., A Unit of Idex Corp.
POWRCOAT—Rectifiers for electropainting. Rapid Power Technologies Inc.
PRAM—Dry stripping system. Pauli Systems
PREDATOR—Automated fume-capture system. Midwest Air Products Co. Inc.
PREKOR—Semibright nickel bath. JacksonLea, A Unit of Jason Inc.
PREP-N-COTE—Iron phosphate coating for steel. Henkel Surface Technologies
PREPAC—Cartridge buff. Schaffner Mfg. Co. Inc.
PREPRITE—Paint stripper. International Specialty Products
PRESS-O-LYTE—Filter press for dewatering sludge. Mid-Western Processes Inc.
PRESTO BLACK—Room temperature blackening process for iron and steel. Birchwood Laboratories Inc.
PRESTO-KLEEN—Metal cleaners. Birchwood Laboratories Inc.
PRO BRITE—Premixed electrolyte for electropolishing. Pro EP
PRO LAB PLATER—Small prototype plating console. Mesa West Inc.
PRO-FIT—Low density polyethylene drum insert. CDF Corp.
PRO-LUB—Additives incorporated into coated abrasives to prevent loading and clogging of abrasive material. Hermes Abrasives Ltd.
PROCESSMASTER—Side-arm automated plating equipment. Enthone-OMI Inc.
PROFILE—Filter element. Pall Corp. Industrial Process Group
PROFINISH—Blast cleaning cabinet. Empire Abrasive Equipment Co.
PROGRAMAT—Automatic plating machine. Enthone-OMI Inc.
PROLAB—Laboratory fume scrubber. Prolite Plastics Ltd.
PROLINE—Plastic piping systems. Asahi/America Inc.
PROMAG—Magnetic-drive centrifugal pumps. Warrender Ltd.
PROMAX—Spray nozzles. *Spraying Systems Co.*
PROQUEL—Fume suppressants. MacDermid Inc.
PROTEC—Immersion heaters. Process Technology Inc.
PROTECTO—Acid-resistant coatings and linings. Dudick Corrosion Proof Inc.
PROTECTOR—Oven temperature regulator. Process Technology Inc.
PROTECTOX—Antitarnish for silver, brass, and gold. Technic Inc.
PROTEDUR—Zinc-iron alkaline, noncyanide plating process. Atotech USA Inc.
PROTEX—Air-dry clear coating for rust protection. Tolber Div., Pyramid Plastics Inc.
PROTEXO-COTE—Strippable protective coating. Thermo-Cote Inc.
PROTOLUX—Alkaline zinc plating processes. Atotech USA Inc.
PROVIS—A process visualization software troubleshooting system for wet processing. Baker Technology Associates Inc.
PULL PLUGS—Molded masking plugs. Duggan Masking Devices
PULSAR—Abrasive blast finishing cabinet. Clemco Industries Corp., Zero Products Div.
PULSE STAR—Pulse-plating power supply. PWR Inc.
PULSEPAK—Pulse-plating power supply. PWR Inc.
PULSETRACK—Finishing bell monitor. ITW Ransburg Electrostatic Systems
PUR-A-GOLD—A gold bath for semiconductor plating. Enthone-OMI Inc.
PURE-FLO—Diatomaceous earth filter aid. Mefiag Div., Met-Pro Corp.
PURIZER—Cleaning solvent recovery system. Procedyne Corp.
PURTREX—Polypropylene filter cartridge. Osmonics Inc.
PYR-AU-BOND—Gold plating process for wire bonding. Enthone-OMI Inc.
PYRAMID—Compressed air purification system. Deltech Engineering Inc.
PYRO-SLUDGE—A packaged paint sludge disposal system. Procedyne Corp.

Q

Q-STRIP—Metal strippers. Chemtech Finishing Systems Inc.
QUAD E—Automatic plating system. American Plating Systems, Div. of Stewart Technologies Inc.
QUALI-LINE—Automatic brightener feeder. ECI Technology Inc.
QUALILAB—Automated CVS analytical instrument with multi-sample capabilities. ECI Technology Inc.
QUALIPLATE—Plating bath analyzer. ECI Technology Inc.
QUANIX—Coating thickness tester. Automation U.S.A.
QUANT STRIPS—Analytical test strips for metal ions. EM Science
QUANTREX—Ultrasonic cleaning system. L&R Mfg. Co.
QUIC—Portable mixer. Indco Inc.
QUICK CLAMP—Printed circuit board finishing rack. Mitchell-Bate Co.
QUICK-CHANGE—Removable-hub contact wheel. Contact Rubber Corp.
QUICKJET—Spray nozzles. Spraying Systems Co.
QUICKSTRIP—Fluid bed stripping system. Tellkamp Systems Inc.
QUIN-COAT—Post-chromate coatings. Chemtech Finishing Systems Inc.
QUIN-LAC—Acrylic-based lacquers. Chemtech Finishing Systems Inc.

QUIN-PREP—Pickling acid additive. Chemtech Finishing Systems Inc.
QUIN-TEC—Cleaners, plating processes, and specialty chemicals. Chemtech Finishing Systems Inc.
QWIK TUBES—Disposable plastic tubes containing activated carbon, ion exchange resin, or both. Sethco Div., Met-Pro Corp.

R

RADIANT SYSTEMS—Zinc plating processes. Tronex Chemical Corp.
RAIL RIDER—Pneumatic lift system for immersion tank lines. Circuit Chemistry Equipment
RAKSTRIP—Additive for use with nitric acid for stripping stainless steel rack tips. MacDermid Inc.
RAMPAGE—Parts washers. USFilter/VL Rampe
RANSOMATIC—Automatic washing machine. CAE Cleaning Technologies
RAYCRON—Radiation-curable coatings. PPG Industries Inc.
RAYMAX—Tubular radiant heater. Watlow Electric Mfg. Co.
RE-ENTRY—Solvent cleaning system. Environmental Solvents Corp.
REACTITROLLER—Programmable process controller. Henkel Surface Technologies
REACTOBOND—Flow or immersion lubricant. Henkel Surface Technologies
READY-COAT—Powder coating system. Nordson Corp., Liquid Systems Group
RECOFLO—Ion exchange equipment. Eco-Tec Inc.
RECOWIN—Electrowinning system. Eco-Tec Inc.
RECYCLE SEAL—Chromium seal rinse. Fremont Industries Inc.
RED DEVIL—Dip treatment for sisal buff. Schaffner Mfg. Co. Inc.
RED-D-VENT—Air-cooled buffing wheels. Munson Machinery Co. Inc.
REDDY RACK—Plating and anodizing racks. National Rack Co.
REDI-RAK—Custom racks with detachable hooks and recessed contact notch system. Adjust-A-Rak Inc.
REFLECTA—Single additive for use in conventional bright nickel plating baths. McGean-Rohco Inc.
REFLECTALLOY—Zinc alloy plating processes. McGean-Rohco Inc.
REFLECTIN—Alloy plating process. MacDermid Inc.
REFLEX—Acid hard-gold bright plating process. Advanced Chemical Co.
REGAL—Gas chlorinators and sulfonators. Chlorinators Inc.
REGALITE—Coated-abrasive belts. 3M Co., Abrasive Systems Div.
RENOCELL—Electrolytic recovery cell. Renovare International Inc.
REPLENISHER—Plating solution feeder. Ivek Corp.
RESINATOR—Portable ion exchange system. Aqualogic Inc.
RESOLVE—Aqueous cleaner systems to replace chlorinated solvents. Enthone-OMI Inc.
RETEC—Heavy metal removal system. USFilter/Memtek
REZKLAD—Acid-resistant epoxy floor coating. Atlas Minerals & Chemicals Inc.
RHODEX—Rhodium plating process. Enthone-OMI Inc.
RHODIUM X-LESS—Compressively-stressed rhodium plating process. Technic Inc.
RHODO BRUSH—Rhodium brush-plating gel. Technic Inc.
RHODOMERSE—Immersion rhodium plating process. Technic Inc.
RHONDIUM—Cyanide-free immersion tin plating process. Tivian Industries Ltd.
RIDOLINE—Alkaline metal cleaners. Henkel Surface Technologies
RIDOSOL—Solvent detergent cleaner additives. Henkel Surface Technologies
RIEHL—Wire brushes. Osborn International, A Unit of Jason Inc.
RIGIBOT—Robot-type transport unit for batch cleaning systems. Crest Ultrasonics Corp.
RIGID FRAME—A titanium anodizing box rack. Servi-Sure Corp.
RILSAN—Polyamide powder coating. Elf Atochem North America Inc.
RIM RUNNER—Automatic hoist transfer system. Technic Inc., Equipment Div.
RINGLOCK—Wheel brushes. Osborn International, A Unit of Jason Inc.
RINGRACK—Anodizing rack. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
RINSE-ALL—Rinse aid to reduce chromium and improve efficiency. Plating Resources Inc.
RINSITE—Rinsing aid. Oakite Products Inc., A Member of The Chemetall Group
RIPPLE ROUND—A lead anode for chromium plating. Alpha Metals Inc.
RIX—Ion exchange module for closed-loop rinsing. M.E. Baker Co.
ROBERTS JET ABRADER—Abrasion resistance test device. Kameras Instruments
ROBERTS—Greaseless buffing compound for satin finishing. JacksonLea, A Unit of Jason Inc.
ROCC—Reactive organic conversion coating. PPG Pretreatment & Specialty Products
ROCHELTEX—Copper addition agent. MacDermid Inc.
RODINE—Pickling inhibitor. Henkel Surface Technologies
RODIP—Chromate conversion coatings and topcoats. McGean-Rohco Inc.
ROGARD PRIME—Protective coating for zinc-plated parts. McGean-Rohco Inc.
ROGLOW—Cyanide zinc plating processes. McGean-Rohco Inc.
ROKIDE—Aluminum oxide, zirconium oxide, zirconium silicate. Norton Co.
ROLL FLOW—Centrifugal disk mass-finishing system. Finishing Associates Inc.
ROLLABRADER—Bench-type tumbler. USFilter/VL Rampe
ROLLBRYT—Burnishing compound. Pax Surface Chemicals Inc.
ROLOC—Twist-locking, color-coded, coated abrasive and nonwoven disks, and accessories. 3M Co., Abrasive Systems Div.
ROMEM—Membrane separation systems. Rasco Inc.
ROMET—Wastewater treatment chemicals. Romar Technologies Inc.
ROMI-KON—Oily wastewater membrane filtration system. Koch Membrane Systems Inc.
RONACLEAN—Cleaners for printed circuit board fabrication. Shipley Ronal
RONACOAT—Organic solderability preservative for surface mount applications. Shipley Ronal
RONAMAX—Electroless nickel process. Shipley Ronal
RONAMERSE—Immersion plating processes. Shipley Ronal
RONAMET—Electroless copper process based on a copper catalyst. Shipley Ronal
RONASCREEN—Thermal and UV-cured solder masks. Shipley Ronal
RONASTAN—Pure tin plating process. Shipley Ronal
RONASTRIP—Tin-lead stripping process. Shipley Ronal
RONOVEL—Range-extended hard-gold plating process. Shipley Ronal
ROSSTECH—CFC-free cleaning solvents. JNJ Industries Inc.
ROSTRIP—Metal strippers. McGean-Rohco Inc.
ROTA-CAT—Electrolytic recovery system. Trionetics Inc.
ROTA-MASTER—Brush. Osborn International, A Unit of Jason Inc.
ROTA-MATIC—Tumbling machines. C&S Engineering Corp.
ROTA-STRIP—Brush. Osborn International, A Unit of Jason Inc.
ROTAL—Electrolytic coloring process for aluminum. Albright & Wilson Americas
ROTEX—Burnishing compounds. Atotech USA Inc.
ROTO-BRITE—Compounds for barrel and vibratory finishing. Roto-Finish Co. Inc.
ROTO-CLONE—Dust collector. Snyder General Corp. American Air Filter
ROTO-FORMS—Ceramic and plastic-bonded media. Roto-Finish Co. Inc.
ROTO-MAX—Centrifugal finishing machine. Roto-Finish Co. Inc.
ROTO-SPIN—Blasting cabinet. Pangborn Corp.
ROTOBLAST—Centrifugal abrasive blasting process. Pangborn Corp.
ROTOSPRAY—Cabinet-type washer. Industrial Washing Machine Corp.
ROTUMBLER—Rotating basket for an ultrasonic cleaning system. Crest Ultrasonics Corp.
ROVELLUX—Barrel nickel plating process. Atotech USA Inc.

ROXIDIZER—System for solvent emission control. Tellkamp Systems Inc.
ROYAL GOLD—Acid gold plating process. Technic Inc.
RUBIN—Acid copper plating process. JacksonLea, A Unit of Jason Inc.
RUFTUF—End brush. Osborn International, A Unit of Jason Inc.
RUST VETO—Rust preventives. Houghton International Inc.
RUSTAWAY—Alkaline descaling compounds. Starlite Technical Service Inc.
RUSTKLEEN—Rust removers. Working Solutions Inc.
RUSTMOVE—Cleaning and rust-removing compound. Chemtech Products Inc.
RUSTRIPPER—Alkaline rust remover. Oakite Products Inc., A Member of The Chemetall Group
RUTHENEX—Ruthenium plating process. Enthone-OMI Inc.
RXPO MODULAR—Power supply units. Controlled Power Co.

S

SAF-SOLV—Cold, nonflammable degreasing solvent. Haviland Products Co.
SAFEGARD—Conversion coating for aluminum. Sanchem Inc.
SAL KORAL—Two-step coloring process for anodized aluminum. Goldschmidt Industrial Chemical Corp.
SAND-O-FLEX—Finishing wheels for contoured surfaces. Merit Abrasive Products Inc.
SANFRAN—Additive for hard anodizing baths. Sanford Process Corp.
SANMASK—Masking material for hard anodizing. Sanford Process Corp.
SAPPHIRE BLUE—Ceramic aluminum oxide abrasive grain used in metal working applications. Hermes Abrasives Ltd.
SAT-N-ETCH—Etchant for aluminum. MacDermid Inc.
SAT-N-MASK—Heavy-duty acid etchant for aluminum. MacDermid Inc.
SAT-TIN—Tin plating process. Shipley Ronal
SATI-BUFF—Buff to produce satin finishes. Schaffner Mfg. Co. Inc.
SATIN BLEND—Nonwoven abrasive. F.L. & J.C. Codman Co.
SATIN SHIELD—Water emulsion blend of waxes. Birchwood Laboratories Inc.
SATIN-FLEX—Flexible wheel. F.L. & J.C. Codman Co.
SATONE—Buffs. Munson Machinery Co. Inc.
SATURN—Bright zinc chloride plating process. Bison Corp.
SATYLITE—Satin nickel plating process. Enthone-OMI Inc.
SCALE-KLEEN—Molten salt descaling. Heatbath Corp.
SCEPTOR—Tubular crossflow inorganic membranes. Graver Technologies Inc.
SCIMITAR—Blasting cabinets. ABB Air Preheater Inc. Ehrsam Blast Systems
SCOPA—Abrasive wheels. Bison Corp.
SCOTCH-BRITE—Cleaning and finishing materials and systems. 3M Co.
SCOTCH—A variety of adhesives, films, and pressure-sensitive tapes. 3M Co.
SCOVIL—Polishing cement. JacksonLea, A Unit of Jason Inc.
SCRATCHBANDS—Hull cell scratch-test panel. Larry King Corp.
SCUF-GARD—End brush. Osborn International, A Unit of Jason Inc.
SCUFF-RITE—Abrasive polishing pad. Louis M. Gerson Co.
SEAL TEX—Phosphate coatings for zinc or iron. Texo Corp.
SECURE—Phosphate coatings. DuBois, Div. of Diversey Lever
SECURIGANTH—Pretreatment cleaners for printed circuitry. Atotech USA Inc.
SEL-REX—Plating processes and equipment. Enthone-OMI Inc.
SELECT COAT—Conformal coating for circuit boards. Nordson Corp., Liquid Systems Group
SELECTO—As a prefix, solid state plating rectifiers. Clinton Power, Subsidiary of Benjamin Power Co.
SELECTRON—Selective plating processes. Sifco Selective Plating, Div. of Sifco Industries Inc.
SELEMION—Ion exchange membranes. Asahi Glass America Inc.
SELEX—Polypropylene cartridge filter. Osmonics Inc.
SELRO—Membrane filtration systems. LCI Corp., Process Div.
SEMISTAR—Semibright nickel plating process. Starlite Technical Service Inc.
SENTRY—Pump and filter system. SERFILCO Ltd.
SEPA—Reverse osmosis membranes. Osmonics Inc.
SERIES COR—Crossflow membrane ultrafiltration module. Koch Membrane Systems Inc.
SERSEAL—Fume suppresant. Henkel Surface Technologies
SHEATH—Water-displacing rust-preventive oil. Birchwood Laboratories Inc.
SHIELDRITE—Conductive water-based coating. BFGoodrich Co., Corzan Industrial Systems Div.
SHINOL—Addition agents for nickel plating. Chemtech Products Inc.
SHOPLINE—Abrasive belts, sheets, disks, and rolls. Carborundum Abrasive Co.
SHORTSTOPPER—Device for preventing shorts in electrostatic spray systems. ITW Ransburg Electrostatic Systems
SHRIVER—Filter presses. Eimco Process Equipment Co.
SIBOT—Side-action brush. Osborn International, A Unit of Jason Inc.
SIGMA 2—Barrel nickel plating process. Atotech USA Inc.
SIGMASCOPE—Conductivity measuring device. Fischer Technology Inc.
SILICARBIDE—Silicon carbide blasting media. Washington Mills Electro Minerals Corp.
SILVA-BRITE—Bright silver plating process. Engelhard Electro Metallics Div.
SILVER GUARD—Antitarnish compound. Technic Inc.
SILVER STREAK—Semibright silver plating process. Technic Inc.
SILVER-GLO—Addition agent for silver plating. Shipley Ronal
SILVER-LUME—A bright silver plating process. Atotech USA Inc.
SILVERBACK—Aqueous cleaner recovery system with ceramic membrane. USFilter/IWT
SILVERGLEAM—Noncyanide silver plating process. Zinex Corp.
SILVERJET—High-speed nonimmersion silver plating process. Shipley Ronal
SILVREX—Bright silver plating process. Enthone-OMI Inc.
SIMICHROME—Metal polish. Competition Chemicals Inc.
SIMPLEX—Electroless nickel plating process. Taskem Inc.
SIR-CUIT—Process for plating through holes in printed circuits. Luster-On Products Inc.
SIT BLASTER—Blasting cabinet. Pressure Blast Mfg. Co. Inc.
SITUFT—Wire brushes. Osborn International, A Unit of Jason Inc.
SKIMMO—Oil/water separator. Hudson Industries Inc.
SLIM-LINE—Horizontal plate filter. Anode Products Co. Inc.
SLOTANIT—Bright acid zinc ammonium-free plating process. Dr. Ing. Max Schlotter
SLOTOCOUP—Acid copper plating process. Dr. Ing. Max Schlotter
SLOTOLET—Fluoride-free tin-lead plating process. Dr. Ing. Max Schlotter
SLOTOLOY—Zinc-nickel alloy coating process. Dr. Ing. Max Schlotter
SLOTOPAL—On-line plating bath controller. Dr. Ing. Max Schlotter
SLOTOPOSIT—Electroless copper plating process. Dr. Ing. Max Schlotter
SLOTOZID—Bright zinc plating process. Dr. Ing. Max Schlotter
SLUDGE GUN—Portable sludge level detector. Markland Specialty Engineering Ltd.
SLURRY-MIZER—Sludge and concentrate dryer. Contaminant Recovery Systems Inc.
SMART OTTO—Automatic plating equipment. M.E. Baker Co.
SMART-TRAK—Remote monitoring and control system for wastewater treatment. DuBois, Div. of Diversey Lever
SMOG-HOG—Air pollution control equipment. United Air Specialists Inc.
SNAP-LOCK—Miniature plating barrels. Singleton Corp.
SNO-FLAKE—Water-wash spray booth compounds, booth coatings, paint strippers, and polishing compounds. Henkel Surface Technologies
SOFT-TOUCH—Speed-controlled centrifugal dryer. Engelhard Electro Metallics Div.
SOL-AL—Aluminum cleaners, etchants, and deoxidizers. Working Solutions Inc.
SOL-U-SALT—Soluble nickel or silver salts. Enthone-OMI Inc.
SOLAR EYE—Irradiation control system for weathering tests. Q-Panel Lab Products
SOLDER-RITE—Tin-lead plating process using a graphite anode basket. Univertical Corp.
SOLDEREX—Tin and tin-lead plating processes. Enthone-OMI Inc.

SOLDERFAST—Tin-lead plating process. Uyemura International Corp.
SOLDERFLO—Peptone-free solder plating process. Atotech USA Inc.
SOLDERMERSE—Immersion solder process. Shipley Ronal
SOLDERON—Nonfluoborate solder plating process. Shipley Ronal
SOLIDEK—Interlocking acid-resistant plastic floor tiles. Dri-Dek Corp.
SOLIPAC—Centrifugal separator. Sanborn Technologies, A Waterlink Co.
SOLOIL—Rust and corrosion preventive oils. Working Solutions Inc.
SOLUBRITE—Brighteners and deoxidizers for aluminum and stainless steel. Working Solutions Inc.
SOLUCOAT—Iron, zinc, and manganese phosphating processes. Working Solutions Inc.
SOLUGOLD—Protective coatings for aluminum, magnesium, and zinc. Working Solutions Inc.
SOLUHIB—Water-based rust and corrosion preventives. Working Solutions Inc.
SOLUKLEEN—General purpose cleaners. Working Solutions Inc.
SOLUSPRAY—Paint spray booth maintenance items. Working Solutions Inc.
SOLUSTRIP—Paint, ink, and adhesive removers. Working Solutions Inc.
SOLUTIONMASTER—Fluorocarbon heat transfer coil. Vulcanium Plating Systems, Div. of Industrial Titanium Corp.
SOLVALL—Solvent blends. Working Solutions Inc.
SOLVE-CARE—Program to guide usage of halogenated solvents. ICI Americas Inc., General Chemicals Dept.
SOLVO-SALVAGER—Solvent recovery distillation system. Westport Environmental Systems
SONICLEAN—Sonic degreasers and generators. Detrex Corp., Equipment Div.
SONOGEN—Ultrasonic cleaners and degreasers. Branson Ultrasonics Corp.
SONOMIST—Spray nozzle. Heat Systems-Ultrasonics Inc.
SPACE-MIZER—Sludge dryer. Contaminant Recovery Systems Inc.
SPACE-SAVER—Titanium anodizing racks. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
SPARKLEEN—Ferrous and nonferrous electrocleaners. A Brite Co.
SPARTAN—Anodizing clamp with porcelain titanium or plain tip. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
SPEC—Electrocoating system. George Koch Sons LLC
SPECLAR—Bright electroless nickel plating system. Pax Surface Chemicals Inc.
SPECTRA—Bright nickel plating process. Shipley Ronal
SPECTROCOLOR—Electrolytic process for coloring aluminum. Henkel Surface Technologies
SPECTRUM—Liquid alkaline cleaners. Chemtech Finishing Systems Inc.
SPECTRUM—Pumable powder cleaning compounds. Henkel Surface Technologies
SPEE-D-BURR—Chemically accelerated deburring system. MacDermid Inc.
SPEE-D-SHEEN—Burnishing compounds. MacDermid Inc.
SPEED-GRIP—Hook and loop back-up pad attachment for abrasive disks. Norton Co.
SPEED-LOK—Quick-change mechanical attachment system for abrasive disks. Norton Co.
SPEEDBUFFER—Oscillating brushing machine. Timesavers Inc.
SPIN FINISH—Mechanical finishing machine and process for decorative finishing. Grav-i-Flo Corp.
SPIRALTEK—Rolled filters. Osmonics Inc.
SPIRATRON—Vibratory finishing machines. Roto-Finish Co. Inc.
SPLIT FINGER—Titanium box anodizing rack. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
SPOTMATIC—Automatic spot gold plating machine. OMG Fidelity
SPRA-GARD—Spray booth coating. OMG Fidelity
SPRAKLEEN—Spray cleaners for ferrous and nonferrous metals. A Brite Co.
SPRAY-LOC—Fume suppressant for chromium plating baths. Accurate Engineering Labs, Div. of Rin Inc.
SPRAYTHRU—Plating barrel with solution pumping capability. Hardwood Line Mfg. Co.
SPREAN—Alkaline spray wash cleaners. Enthone-OMI Inc.
SPREX—Wetting agent and aluminum etchant. DuBois, Div. of Diversey Lever
SRHS—Hard chromium plating process. Atotech USA Inc.
SST (SLIDERAIL SQUARE TRANSFER)—Electrocoat paint finishing system. Therma-Tron-X Inc.
STABUFF—Electroless nickel plating process. MacDermid Inc.
STAK-PAK—Tote pans for mass-finishing machines. C&S Engineering Corp.
STANNAL—Electrolytic coloring process for aluminum. Albright & Wilson Americas
STANNO-BRUSH—Tin brush-plating gel. Technic Inc.
STANNO-SPEED—Tin plating process. Atotech USA Inc.
STANNOLUME—Bright acid tin plating process. Atotech USA Inc.
STANNOSTAR—Bright acid tin plating process. Enthone-OMI Inc.
STANOBOND—Bronze immersion coating. Henkel Surface Technologies
STANODINE—Immersion tin process. Henkel Surface Technologies
STANOMERSE—Immersion tin. Technic Inc.
STANZEC—Tin-zinc plating process. Atotech USA Inc.
STAR BLAST—Staurolite abrasive blasting material. DuPont Co.
STARGLO—Tin and tin-lead plating processes. Taskem Inc.
STEEL CORE—Construction feature of plating barrels. Singleton Corp.
STEELCOTE—Phosphate coatings. ACI Chemicals Inc.
STEELSHINE—Buffing compounds for stainless steel. Matchless Metal Polish Co.
STEINEMANN—Pressure curtain coater. George Koch Sons LLC
STERLING—Portable plating barrel. Sterling Systems Sales Corp.
STILBAG—Liner for solvent recovery equipment. Finish Thompson Inc.
STINGER—Wastewater sampler. Isco Inc., Environmental Div.
STRAT-O-SHEEN—Burnishing compounds. JacksonLea, A Unit of Jason Inc.
STRATAVAP—Wiped thin-film evaporator. Licon Inc.
STRATOLUX—Bright nickel plating process. Atotech USA Inc.
STREAKER—Split rail production machine. Walgren Co.
STRESS TABS—Test panels for determination of plated deposit stress. Larry King Corp.
STRETCHCOAT—In-mold powder coating. Elf Atochem North America Inc.
STRIP-AID—Immersion stripping compound. MacDermid Inc.
STRIPMASTER—Portable dry stripping system. Envirosystems Equipment Co. Inc.
STRIPODE—Nickel stripping agent. Luster-On Products Inc.
STRIPOL—Metal strippers. Hubbard-Hall Inc.
STRYPP—Hot tank paint stripper. DuBois, Div. of Diversey Lever
SUB-O-MATIC—Submerged automatic finishing equipment. Almco Inc.
SUB-X—Submerged filter system. Sethco Div., Met-Pro Corp.
SUBSTAR—Zincating solution for plating on aluminum. Okuno Chemical Industries Co. Ltd.
SULFAMEX—Nickel plating chemicals. Enthone-OMI Inc.
SULFATRONIX—Nickel sulfamate plating processes. Atotech USA Inc.
SULFEX—Waste treatment process for removing heavy metals. USFilter/Permutit
SUMMA—Electropolishing processes and equipment. Molectrics Inc.
SUMP-GARD—Plastic sump pump. Vanton Pump & Equipment Corp.
SUN-CHEX—Xenon exposure system that replicates effects of sun exposure. Atlas Electric Devices Co.
SUN-NI—Electroless nickel plating process. Hubbard-Hall Inc.
SUNCURE—Screen printable solder mask. Alpha Metals Inc.
SUP-R-TANK—Heavy duty pickling tank. Goad Co.
SUPALEX—Bright nickel plating process. Albright & Wilson Americas
SUPARATOR—Oil recovery system for aqueous cleaners. Aqueous Recovery Resources Inc.
SUPER COMPACT—Flow-through wastewater treatment system. Advanced Chemical Systems Inc.
SUPER DISC—Titanium anodizing rack. Servi-Sure Corp.
SUPER DROPOUT—Wastewater precipitation agent. A Brite Co.

SUPER MAX—Bright nickel plating process. Atotech USA Inc.
SUPER MISTROL—Mist and fume suppressant. Bison Corp.
SUPER PYROBRITE—Bright copper plating process. Albright & Wilson Americas
SUPER SAMSON PLUS—Centrifugal dryer. Atotech USA Inc.
SUPER SEALTITE—Cold sealing process for anodized aluminum. Goldschmidt Industrial Chemical Corp.
SUPER-DUTY—Plating barrels. Singleton Corp.
SUPER-MIL—Emulsion cleaner for removing all soils in industrial spray washers. DuBois, Div. of Diversey Lever
SUPER-MIR—Nickel plating brighteners. Plating Resources Inc.
SUPER-STARLITE—Bright nickel plating process. Starlite Technical Service Inc.
SUPERANTIK—Oxidizing agent for brass, bronze, and copper. Sur-Fin Chemical Corp.
SUPERBLACK—Noniridescent black coating. Pavco Inc.
SUPERBLAST—Portable blast cleaning pot. Empire Abrasive Equipment Co.
SUPERCAP—Large capacity tanks. Tri-Mer Corp.
SUPERCHANGER—Plate-and-frame heat exchanger. Tranter Inc.
SUPERFLEX—Set-up polishing wheel. Munson Machinery Co. Inc.
SUPERFLO—Parts washer circulation pump. Graymills Corp.
SUPERGARD—Corrosion inhibitor. Pavco Inc.
SUPERLUME—Bright nickel plating process. Atotech USA Inc.
SUPERSEAL—Conversion coating. Pavco Inc.
SUPERSHEEN—Deburring and finishing processes, equipment, and supplies. Almco Inc.
SUPERTARTRAL—Additive for cyanide copper plating processes. Shipley Ronal
SUPERTUF—Plating barrel. Engelhard Electro Metallics Div.
SUPERZINC—Zinc alloy plating processes. MacDermid Inc.
SUPRAFILT—Filtration equipment. Industrial Filter & Pump Mfg. Co.
SUPRAGAL HYPER—Bright nickel plating process. Dr. Hesse & Cie.
SUPREME—Bright nickel plating process. Atotech USA Inc.
SUR COAT—Conversion coating process. Coral Chemical Co.
SURCOAT—Chromate coating for aluminum. Sur-Fin Chemical Corp.
SURE CURE PLUS—Infrared oven system with moveable walls. Ciscan Industries Ltd.
SURE-CLEAN—Conveyor-type parts washer. CAE Cleaning Technologies
SURE-FIT—Drop-in liner. C&M Liner Co. Inc.
SURE-FLO—Blast media regulator. Empire Abrasive Equipment Co.
SURFACESCAN—Surface analyzer based on SERA technology. ECI Technology Inc.
SURFCAT—Catalyst for electroless plating. Surface Technology Inc.
SURFCHEM—Defoaming agent. Pax Surface Chemicals Inc.
SURFLAC—Water-based coatings. Pax Surface Chemicals Inc.
SURFWET—Adsorption modifiers for nonconductive substrates. Surface Technology Inc.
SWEEPZONE—Sweep frequency system for ultrasonic cleaners. L&R Mfg. Co.
SYGEF—Pipe, valves, and fittings of polyvinylidene fluoride. George Fischer Inc.
SYN-KOTE—Spray booth compound. Calgon Corp.
SYNFLEX—Polishing wheels. Spartan Felt Co.

T

T-PHOS—Copper anodes. International Metals and Chemicals Group
TAC—Prefix used for processes and equipment related to the anodizing of aluminum. Okuno Chemical Industries Co. Ltd.
TAGNITE—Process for anodizing magnesium. Technology Applications Group Inc.
TAMCO—Polyethylene plating and storage tanks. U.S. Plastic Corp.
TARNIBAN—Antitarnish for silver and copper. Technic Inc.
TARNISH GUARD—Two-step tarnish preventive. Patclin Chemical Co. Inc.
TART—Acid cleaner for removing light rust and scale. DuBois, Div. of Diversey Lever
TASOX—Inhibitor for use in acid pickling and stripping solutions. Taskem Inc.
TECAM—Fluid bed rack stripping equipment. Techne Inc.
TECH-TIN—Immersion tin solution. Technic Inc.
TECHNI-PLUS—Plastic lining materials. Koch Engineering Co. Inc.
TECHOSOL—Burnishing soap. Technic Inc.
TECTRON—Flushable cathode cell for electrocoating. UFS Corp.
TEFLON—Nonstick finish. DuPont Co.
TEFZEL—Powder coatings. DuPont Co.
TELMEC—Tab plating equipment. Degussa Hüls Corp.
TEMP-PLATE—Heat transfer panels. Paul Mueller Co.
TEMP-R-TAPE—Tape for use in gold plating. Furon CHR
TEMP-X-CHANGER—Heat exchanger. United Air Specialists Inc.
TEMPEST—Jet-spray parts cleaner. Graymills Corp.
TERG-A-ZYME—Cleaning compound. Alconox Inc.
TERJ—Metal cleaning compound. DuBois, Div. of Diversey Lever
TERMINATOR—Fume hood. Midwest Air Products Co. Inc.
THERMAL MASTER—Shell-and-tube heat exchanger. Vulcanium Plating Systems, Div. of Industrial Titanium Corp.
THERMASOL—Halogenated nonflammable cleaning solvent. Thermo-Cote Inc.
THERMERSION—Fused quartz immersion heater. Sethco Div., Met-Pro Corp.
THERMORON—Heat exchangers. Norton Performance Plastics Corp.
THINKER BOY—Plating rack sections. Belke Mfg. Co.
THRUNIC—Nickel plating processes. Uyemura International Corp.
TI CORE—Titanium-covered aluminum bar. Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
TIGER GRIT—Abrasive disks and flap wheels. Felton Brush Inc.
TIGER—Greaseless buffing compound. Matchless Metal Polish Co.
TIGOLD—Titanium nitride coating system. Ulvac, North American Corp.
TIN SOL—Maintains tin in stannate solutions. Atotech USA Inc.
TIN-MIR—Tin plating brighteners. Plating Resources Inc.
TINOLS—Bright tin and tin-lead plating processes. Maclee Chemical Co. Inc.
TINOMATS—Satin tin and tin-lead plating processes. Maclee Chemical Co. Inc.
TINPOSIT—Immersion tin process. Shipley Ronal
TINTAC—Water-soluble vinyl protective film. MacDermid Inc.
TODD—Integrated process control system. Parker Systems, Div. of D.J. Parker Co.
TONKAFLO—Multistage centrifugal pumps for reverse osmosis. Osmonics Inc.
TOP CATCH—Waste treatment chemicals. Okuno Chemical Industries Co. Ltd.
TOP LUCINA—Additives for printed circuit board plating processes. Okuno Chemical Industries Co. Ltd.
TOP SEAL—Anodizing sealant. Okuno Chemical Industries Co. Ltd.
TOP-ACNA—Nickel brightener. Okuno Chemical Industries Co. Ltd.
TOPAS—Noncyanide alkaline electrolyte. JacksonLea, A Unit of Jason Inc.
TOPEX—Satin finishing wheel. Bison Corp.
TOPGUN—High-velocity, oxygen-fuel thermal spray process. Miller Thermal Inc.
TOPMET—Vacuum web coater. Leybold Systems Inc.
TOPO—Nylon abrasive wheels. Bison Corp.
TOREX—Vibratory finishing systems. Delrod Sales Corp.
TOTALIZER—Ampere-hour meter. Mesa West Inc.
TOTALSTAT—Electrostatic coil coating system. United Air Specialists Inc.
TRACE MET—Bench-top elemental analyzer. Metorex Inc.
TRACKER—Side-arm hoist. Plasfab Inc.
TRANSVAP—Mobile self-contained evaporation system. Licon Inc.
TRI-AXIS—Robotic transfer system for selective plating. Technic Inc., Equipment Div.
TRI-BLUE—Protective coating for zinc plate. Luster-On Products Inc.
TRI-COAT—Multicoat vacuum coating system. Stokes Vacuum Inc.
TRI-ETHANE—Stabilized trichloroethane for cold degreasing. PPG Industries Inc.

TRI-MAX—Multicomponent liquid cleaner system. McGean-Rohco Inc.
TRI-NI—High-sulfur nickel strike. Enthone-OMI Inc.
TRI-PAK—Batch oven with built-in fume incinerator and heat recovery system. Precision Quincy Corp.
TRI-SEAL—Conveyorized solvent degreaser utilizing high pressure sprays. Detrex Corp., Equipment Div.
TRIBOL—Wear-resistant electroless coatings. Stapleton Technologies
TRIBRITE—Blue-bright conversion coating for zinc. Accurate Engineering Labs, Div. of Rin Inc.
TRICHROME PLUS—Trivalent chromium plating process. Atotech USA Inc.
TRICHROME SMOKE—Trivalent chromium plating process to deposit transparent, gray coatings on nickel plate. Atotech USA Inc.
TRICLENE—Trichloroethylene vapor degreasing solvent. Metal Coatings International Inc.
TRICROLYTE—Trivalent chromium plating process. Enthone-OMI Inc.
TRIDACATOR—pH papers. Fil-Chem Inc., Paul Frank Div.
TRIDIP—Trivalent chromate conversion coating. A Brite Co.
TRIDUR—Chromates. Atotech USA Inc.
TRILYTE—Trivalent chromium plating process. Enthone-OMI Inc.
TRIMAC—Decorative trivalent chromium plating process. MacDermid Inc.
TRIPLEE—Buffing compounds for nonferrous metals and plastics. Matchless Metal Polish Co.
TRITEC—Plasma-assisted sputtering system. Leybold Systems Inc.
TRU-SWEEP—Ultrasonic generator. Crest Ultrasonics Corp.
TRU—Phosphated test panels. ACT Laboratories Inc.
TRULOCK—Crimped wire wheel. Weiler Corp.
TRUSHADE—Gold plating process. Technic Inc.
TUFCOTE—High-solids baking enamel. DuPont Co.
TUFF TANKS—Containers for hazardous chemicals. Hoover Container Sales & Service Inc., Sub. of Hoover Group Inc.
TUFF-CLAMP—Anodizing clamp. Leed Himmel
TUFF-TUBE—Thermoplastic-coated stainless steel heater. Chromalox
TUFMATIC—Short-trim knot-style brushes. Osborn International, A Unit of Jason Inc.
TUFTAN—Wear-resistant vinyl plastisol mass-finishing liner. USFilter/VL Rampe
TUMB-L-MATIC—Multiple barrel finishing units. John R. Nielsen & Sons Inc.
TUMBLAST—Batch-type abrasive blast cleaning machine. USFilter/Wheelabrator
TUMBLEBRYTE—Burnishing compounds. Pax Surface Chemicals Inc.
TUMBLEPLATER—Replacement for conventional barrel plating. Technic Inc., Equipment Div.
TUMBLEX—Preformed high density tumbling media. Polyflow Inc.
TURBO-CHARGER—Parts washer. Bowden Industries Inc.
TURBO—Bright nickel plating process. Enthone-OMI Inc.
TURBOBELL—Rotary spray atomizer. ITW Ransburg Electrostatic Systems
TURBODISK—Turbine-driven rotator for electrostatic painting. ITW Ransburg Electrostatic Systems
TURBOTREATER—Vacuum furnace. Ipsen International Inc.
TWIN EAGLE—Hoist system. American Plating Systems, Div. of Stewart Technologies Inc.
TY BRUSHES—Rubber-bonded wire brushes. Osborn International, A Unit of Jason Inc.
TY-FLEX—End brush. Osborn International, A Unit of Jason Inc.
TY-NEE—Small tumbling barrel. A.E. Aubin Co.
TYNEX—Abrasive-impregnated nylon filaments. DuPont Polymers Filament Products

U

UBAC—Acid copper plating process. Enthone-OMI Inc.
UDIQUE—Metallizing systems for plastics. Enthone-OMI Inc.
UDYLITE—Plating processes and equipment. Enthone-OMI Inc.
ULTIMATIC—DC rectifier. Aldonex Inc.
ULTRA BRITE—Tin plating process. Alchem Corp.
ULTRA GRIT—Abrasive brushes. Osborn International, A Unit of Jason Inc.
ULTRA STAN—Matte acid tin plating process. Atotech USA Inc.
ULTRA-BLAK—Black oxide finish. Electrochemical Products Inc. (EPI)
ULTRA-BLEND—Buffing wheel. JacksonLea, A Unit of Jason Inc.
ULTRA-COR—Membrane for electrocoat paint recovery. Koch Membrane Systems Inc.
ULTRA-LIFE—Platinized anodes. De Nora North America Inc.
ULTRA-LIFE—Platinized titanium anode. Engelhard Electro Metallics Div.
ULTRA-LITE—Bright nickel plating process. Enthone-OMI Inc.
ULTRA-PLATE—Electroless copper plating process for printed circuit boards. OMG Fidelity
ULTRA-PULSE—Pulse-plating power supply with square wave output. Clinton Power, Subsidiary of Benjamin Power Co.
ULTRA-RAD—Gas-fired infrared dryer. Eclipse Combustion Inc.
ULTRA-SHEEN—Liquid burnishing compound. JacksonLea, A Unit of Jason Inc.
ULTRA-STACK—Modularized silicon diode replacement kit. Clinton Power, Subsidiary of Benjamin Power Co.
ULTRA-TECH—Phosphate for high corrosion resistance. JacksonLea, A Unit of Jason Inc.
ULTRA-TEK—Cartridge filter media. Donaldson Co. Inc., Torit Products
ULTRA-WEB—Cartridge filter media. Donaldson Co. Inc., Torit Products
ULTRA—Additive for acid chloride zinc plating. Taskem Inc.
ULTRALEVEL—Bright nickel plating process. Pax Surface Chemicals Inc.
ULTRALITE—Lightweight ceramic mass-finishing media. Ultramatic Equipment Co.
ULTRALON—Nonstick fluoropolymer coatings. Whitford Corp.
ULTRALOY—Tin-nickel plating process. Electrochemicals
ULTRALOY—Zinc-cobalt plating process. Alchem Corp.
ULTRALUME—Nickel plating process. Alchem Corp.
ULTRAMATE—Corrision inhibiting oils. Chemtech Finishing Systems Inc.
ULTRAMATIC—Chain-driven side-arm plating machine. Upton Industries Inc.
ULTRAPHOS—Phosphate coating processes. Chemtech Finishing Systems Inc.
ULTRASEAL—Leachant sealant for chromates. MacDermid Inc.
ULTRASEP—Tubular ultrafiltration system. R-V Industries Inc.
ULTRASTRIP—Paint strippers. MacDermid Inc.
ULTREX—Metal cleaners. Enequist Chemical Co. Inc.
UNI KLEEN—Metal cleaners. Heatbath Corp.
UNI-COLOR—Rectifier for electrolytic coloring of anodized aluminum. Dynapower Corp.
UNI-FINISHER—Nylon wheel sanding machine. Union Tool Corp.
UNI-MASTER—Scrubber brushes. Osborn International, A Unit of Jason Inc.
UNIBRITE—Bright nickel plating process. Atotech USA Inc.
UNICHROME—Chromium plating process, copper plating process, and conversion coatings. Atotech USA Inc.
UNICLEAN—Metal cleaning processes. Atotech USA Inc.
UNIFILTER—Sludge dryer. Delta Pollution Control Inc.
UNIFOG—Environmental testing equipment. Atotech USA Inc.
UNIVERSAL—pH indicating controller. Analytical Measurements Inc.
UVCON—Accelerated weathering tester. Atlas Electric Devices Co.

V

VAC-SEAL—Leakproof seal for plating racks. Belke Mfg. Co.
VACULOY—Tin-lead solder anodes. Alpha Metals Inc.
VACUTEC—Evaporation targets. Atomergic Chemetals Corp.
VAND-ALLOY—Electroless nickel plating processes. MacDermid Inc.
VAND-ALOY—Electroless nickel plating process. Cemco International Inc., A Div. of Vanguard Holdings Inc.
VAPORMATT—Liquid abrasive blasting equipment. Kleiber & Schulz Inc.
VARIAS—Cyanide zinc plating process. JacksonLea, A Unit of Jason Inc.
VARIOCLEAN—Parts cleaning system. Ipsen International Inc.
VECTOR—Washing machines with high velocity solution movement. Ramco Equipment Corp.
VEDOC—Powder coatings. Ferro Corp., Powder Coatings Div.
VEEJET—Spray nozzles. Spraying Systems Co.
VELOURS—Satin nickel plating process. Atotech USA Inc.

VENMET—Solution for metal removal from wastewater. Morton International Inc., Ventron Div.
VERSA-COAT—Manual powder spray booth. Nordson Corp., Liquid Systems Group
VERSA-SPRAY—Mobile powder coating system. Nordson Corp., Liquid Systems Group
VERSADUR—Extruded thermoplastic sheet. HPG International Inc.
VERSAMATIC—Strip plating equipment. Cemco International Inc., A Div. of Vanguard Holdings Inc.
VERSEYBLACK—Deep dark finish over brass. Zinex Corp.
VERTIFLO—Line of vertical pumps. Fluidpak Inc.
VERTREL—Cleaning solvents. Detrex Corp., Solvents and Environmental Services Div.
VESPER—Filter press system. Kontek Ecology Systems Inc.
VI-BRADER—Vibratory mass-finishing equipment. USFilter/VL Rampe
VIBARREL—Vibratory plating equipment. ECI Technology Inc.
VIBRA SHAKE—Dust collector. Donaldson Co. Inc., Torit Products
VIBRA-BURR—Vibratory deburring and finishing equipment. Ultramatic Equipment Co.
VIBRA—Plating barrel. Manz Galvano-Technik GmbH
VIBREX—Vibrating plating barrel. AmeriChem Engineering Services
VIBRO-ENERGY—Vibratory finishing equipment. Sweco Inc.
VIBROBOT—Automatic bulk plating machine. Cemco International Inc., A Div. of Vanguard Holdings Inc.
VIBROWEN—High performance vibratory plating system. International Surface Technology Ltd.
VIBURR-MATIC—Vibratory finishing machine. C&S Engineering Corp.
VIRGO—Fused salt bath for descaling, desanding, and degraphitizing for steels and alloys. Occidental Chemical Corp.
VIRO-BLACK—Deep dark finish over nickel. Zinex Corp.
VIRO-BRASS—Bright brass plating process for rack work. Zinex Corp.
VIRO-BRASS—Noncyanide, bright brass plating process. Mibus Inc.
VIRO-CLEAN—Degreasing cleaner. Zinex Corp.
VIRO-GOLD—Noncyanide gold plating process. Zinex Corp.
VISSTRIP—*Viscous paint stripper. Oakite Products Inc.*, A Member of The Chemetall Group
VISTABRITE—Brighteners for nickel plating. Pax Surface Chemicals Inc.
VISTAWETTER—Additive and antipitting agent for nickel plating. Pax Surface Chemicals Inc.
VOLTOSTRIP—Electrolytic stripper. MacDermid Inc.
VONNEGUT—Belt polishers and brush-backed polishing heads. *Grinding & Polishing Machinery Corp.*
VORTEX—Doorless plating barrel. Hardwood Line Mfg. Co.
VORTEX—Ultrasonic cleaning system. Zenith Ultrasonics Inc.
VORTRON—Centrifugal disk finishing machine. Harper Surface Finishing Systems Inc.
VULCAN—Abrasive fiber disk coated with ceramic aluminum oxide. Norton Co.
VYNAGRIP—Flexible PVC duckboard. Tepromark International Inc.

W

WAGGLER—Motor to impart oscillation in powder coating system. ITW Gema
WALLCOAT—Paint booth coatings. Haviland Products Co.
WASTEWARRIOR—Ultrafiltration system. Hyde Products Inc., MonlanGroup Div. of Lafourche Mfg.
WATCHDOG—A self-contained printed circuit board to monitor SCR performance in power supplies. Rapid Power Technologies Inc.
WATER-OFF—Water-displacing corrosion inhibitors. Haviland Products Co.
WATERSHED—Water-soluble rust preventive and rinsing aid. Heatbath Corp.
WATT-SAVER—Plating rectifier. Dynapower Corp.
WEATHER-OMETER—Accelerated weathering tester. Atlas Electric Devices Co.
WEBRAX—Resin and grain-impregnated nonwoven abrasive web. Hermes Abrasives Ltd.
WET-ALL—Surfactants and rinsing aids. Plating Resources Inc.
WETAID—Wetting agents. Heatbath Corp.
WHALE—Air-operated pump. Industrial Filter & Pump Mfg. Co.
WHEEL GUARD—Process for plating aluminum wheels. MacDermid Inc.
WHIRL/WET—Fume scrubber for wet particulates. Tri-Mer Corp.
WHIRLJET—Hollow-cone spray nozzles. Spraying Systems Co.
WHIRLWIND—Ventilated buff. Stan Sax Corp.
WHITE DIAMOND—Buffing composition. Matchless Metal Polish Co.
WHITE KNIGHT—Oil filtration system. SERFILCO Ltd.
WIN—Abrasive nozzle for wet abrasive blasting. Boride Products Inc.
WINDJET—Spray nozzles. Spraying Systems Co.
WINLINE—Degreasers, dryers, and stills. Finishing Equipment Inc.
WOLFHEAD—Brush-backed abrasive wheel. Grinding & Polishing Machinery Corp.

X

X-BUG—Electrolytic recovery system. Precious Metals Processing Consultants Inc.
X-MET—Chemical analyzers and thickness gauges. Metorex Inc.
X-VAR—Wire stripper. OMG Fidelity
XCELBLAST—Airblast cabinet. Pangborn Corp.
XENITH MATRIX—Zinc-iron alloy plating process. Taskem Inc.
XENITH PARAGON—Alkaline zinc alloy plating processes. Taskem Inc.
XENITH PINNACLE—Acid zinc alloy plating processes. Taskem Inc.
XENITH—Noncyanide zinc plating process. Taskem Inc.
XYLAC—High-solids and waterborne decorative enamels. Whitford Corp.
XYLAN—Low-friction fluoropolymer coatings and dry-film lubricants. Whitford Corp.

Y

YELLOW H—Chromate conversion coating. Pavco Inc.

Z

Z PLATE—Alkaline noncyanide plating bath concentrate. Pax Surface Chemicals Inc.
Z-BOND—Zincating compound for aluminum. Pax Surface *Chemicals Inc.*
Z-GUARD—High-speed tin plating process. Mibus Inc.
ZEBRA—Flap polishing wheels. Even Cut Abrasive Co.
ZENON—Closed-loop water system. Kyzen Corp.
ZEO-KARB—Ion exchange resin. USFilter/Permutit
ZERO MIST—Surface additive to control chromium mist and spray. Enthone-OMI Inc.
ZEROCHROME—Replacement for hexavalent and trivalent *chromium plating. Zinex Corp.*
ZETA ONE—Deburring robot. Harper Surface Finishing Systems Inc.
ZINC GLO—Zinc plating process. Alchem Corp.
ZINC-AID—Zinc brightener and plating process. Pavco Inc.
ZINC-AL—Alkaline bright zinc plating process. Shipley Ronal
ZINC-MIR—Zinc plating brighteners. Plating Resources Inc.
ZINCAD—Zinc and cadmium plating purification equipment. Summit Scientific Corp.
ZINCALUX—Bright acid zinc plating process. Atotech USA Inc.
ZINCO BRITE—Zinc-cobalt plating process. Alchem Corp.
ZINCONAL—Zincate immersion plating process for aluminum. Hubbard-Hall Inc.
ZINCROLYTE—Zinc alloy plating processes. Enthone-OMI Inc.
ZINEXC—Acid chloride zinc plating process. American Chemical & Equipment
ZINIC—Zinc-nickel plating process. MacDermid Inc.
ZINKONAL SUPER—Cyanide zinc plating process. Dr. Hesse & Cie.
ZINKOR—Bright alkaline cyanide-free zinc plating process. Dr. Hesse & Cie.
ZIP-TIP—Quick-disconnect spray nozzles. Bex Inc.
ZIPPO—Buffs and compounds. Formax Mfg. Corp.
ZIPSOL—Solvent cleaner. OMG Fidelity
ZIRBLAST—Ceramic blasting media. SEPR Ceramic Beads & Powders
ZIRSHOT—Ceramic bead blasting media. SEPR Ceramic Beads & Powders
ZIRTEX—Multiface abrasive disk. Bison Corp.
ZODIAC—Bright nickel plating process. Atotech USA Inc.
ZYLITE—Acid zinc plating process. Atotech USA Inc.

PRODUCT, PROCESS AND SERVICE DIRECTORY

Manufacturers of finishing products and suppliers of finishing processes and services wishing to be listed in this directory should forward their request in writing to the editor. Companies in bold face are advertisers in this edition.

ABRASIVE BLASTING—See Blasting

ABRASIVE DISKS

Abtex Corp.
American Siepmann
Anderson Products Inc., Subsidiary of Wilton Corp.
Bison Corp.
Buffalo Abrasives
Carborundum Abrasive Co.
Duraline Abrasives Inc.
Even Cut Abrasive Co.
Felton Brush Inc.
Formax Mfg. Corp.
Glassmaster Monofilament Div.
Graves Co.
Hermes Abrasives Ltd.
Iding Co. Inc., M.P.
Klingspor Abrasives Inc.
Lake Country Mfg. Inc.
Merit Abrasive Products Inc.
Metabo Corp.
Norton Co.
Osborn International, A Unit of Jason Inc.
Rex-Cut Products Inc.
Schaffner Mfg. Co. Inc.
Spartan Felt Co.
Standard Abrasives Inc.
3M Co., Abrasive Systems Div.
United Abrasive Inc.
Weiler Corp.

ABRASIVE FLOW FINISHING EQUIPMENT

Dynetics Corp.
Extrude Hone Corp.
Kleiber & Schulz Inc.
Schaffner Mfg. Co. Inc.

ABRASIVE POWDERS

Brent America Inc.
Darmann Abrasive Products
Dedeco International Inc.
Electro Abrasives Corp.
K.C. Abrasive Co. Inc.
Meller Optics Inc.
SEPR Ceramic Beads & Powders
United Abrasive Inc.
Washington Mills Electro Minerals

ABRASIVE WHEELS, RESINOID, FELT, OR RUBBER BONDED

Abtex Corp.
American Siepmann
Anderson Products Inc., Subsidiary of Wilton Corp.
Bison Corp.
Brandywine Abrasives
CIMID
Camel Grinding Wheels
Carborundum Abrasive Co.
Codman Co., F.L. & J.C.
Darmann Abrasive Products
Divine Brothers Co.
Duraline Abrasives Inc.
Even Cut Abrasive Co.
Formax Mfg. Corp.
Gerson Co., Louis M.
Graves Co.
Iding Co. Inc., M.P.
Metabo Corp.
Norton Co.
Osborn International, A Unit of Jason Inc.
Rex-Cut Products Inc.
Schaffner Mfg. Co. Inc.
Spartan Felt Co.
Standard Abrasives Inc.
3M Co., Abrasive Systems Div.
United Abrasive Inc.
Yerges Mfg. Co.

ACID SALTS—See Pickling and Bright Dipping Processes

ACTIVATORS—See Pickling and Bright Dipping Processes

AGITATORS—See Mixing and Agitating Equipment

AIR POLLUTION CONTROL EQUIPMENT

Cyclones

Aget Mfg. Co.
Grinding & Polishing Machinery Corp.
Hammond Machinery Inc.
Sternvent Co. Inc.
United Air Specialists Inc.

Filters

Aercology Inc.
Aget Mfg. Co.
Air Quality Engineering Inc.
Ceco Filters Inc.
Champion Laboratories Inc.
Conserve Engineering Co. LLC
DCE Inc.
Donaldson Co. Inc., Torit Products
Envirosystems Equipment Co. Inc.
Hammond Machinery Inc.
Jet Air Technologies
Kalamazoo Industries
Midwest Air Products Co. Inc.
ScrubAir Vent Systems Inc.
Snyder General Corp., American Air Filter
Steelcraft Corp.
Sternvent Co. Inc.
United Air Specialists Inc.

Mist Eliminators

Aget Mfg. Co.
Ceco Filters Inc.
ChromeTech Inc.
Conserve Engineering Co. LLC LLC
Fabco Plastics Wholesale Ltd.
ITW Vortec
Industrial Plastics Fabricators Ltd.
KCH Services Inc.
Kimre Inc.
Midwest Air Products Co. Inc.
Monroe Environmental Corp.
Polyfab Plastics & Supply
Prolite Plastics Ltd.
ScrubAir Vent Systems Inc.
Sumrack Equipment and Supply Co. Inc. (SESCO)

Scrubbers

AB Plastics Inc.
Air Chem Systems Inc.
Automate Tech Inc.
Belding Tank Technologies Inc.
Calfran International Inc.
Ceco Filters Inc.
Ceilcote Air Pollution Control
Compliance Systems International
Conserve Engineering Co. LLC
Duall Div., Met-Pro Corp.
Eltek of Rochester Inc.
Excel Plating Technology Inc.
Fab-Tech
Fabco Plastics Wholesale Ltd.
Fabrication Technologies International. Ltd.
Fisher-Klosterman Inc.
Goad Co.
Grewe Plastics

Harrington Industrial Plastics Inc.
Harrison Plastic Systems Inc.
Industrial Plastics Fabricators Ltd.
Intellect Systems & Marketing Inc.
Jet Air Technologies
KCH Services Inc.
Kimre Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Mid-America Plastics
Midwest Air Products Co. Inc.
Misonix Inc.
Monroe Environmental Corp.
NCA Systems Inc.
P.G. Industries Inc.
Plastech Inc.
Poly Products Corp.
Polyfab Plastics & Supply
Pro Ep
Pro-Fab Mfg. Inc.
Prolite Plastics Ltd.
R-V Industries Inc.
S&K Products International
ScrubAir Vent Systems Inc.
Snyder General Corp., American Air Filter
Stein & Associates Inc., Norman
Sumrack Equipment and Supply Co. Inc. (SESCO)
Technic Inc., Equipment Div.
Tri-Mer Corp.
TriTech Technologies Inc.
Vanaire Ltd.
Viatec/Hastings Engineered Systems
Viron International

ALUMINUM, PROCESSES FOR PLATING ON

Accurate Engineering Labs, Div. of Rin Inc.
Acme Metal Finishing Co. Inc.
Atotech USA Inc.
Brent America Inc.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemical Solvents Inc.
Chemtech Finishing Systems Inc.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Heatbath Corp.
Henkel Surface Technologies
Hubard-Hall Inc.
Ipsen International Inc.
JacksonLea, A Unit of Jason Inc.
Kurts & Wolfe Chemical Co. Inc.
LeKem Inc.
Liquid Development Co.
MacDermid Inc.
McGean-Rohco Inc.
OMG Fidelity
Okuno Chemical Industries Co. Ltd.
Pax Surface Chemicals Inc.
Plating Resources Inc.
Rin Inc.
Shipley Ronal
Sur-Fin Chemical Corp.
Taskem Inc.
Technic Inc.
Triple-S Chemical Products Inc.
U.S. Specialty Color Corp.
Working Solutions Inc.

AMMETERS AND AMPERE-HOUR METERS—See Electrical Metering Equipment

ANALYTICAL EQUIPMENT—See Testing Equipment

ANODE ACCESSORIES

Bags

Ames Metal Products Co.
Anode Products Co. Inc.
Atotech USA Inc.
Bison Corp.
Canfield Technologies Inc.
Chemtech Finishing Systems Inc.
Kurts & Wolfe Chemical Co. Inc.
Met-Chem Inc.
Plating Products Co. Inc.
Plating Supplies International Inc.
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
Titan International Inc.
Univertical Corp.

Baskets and Hooks

Able Rack Co.
Accurate Rack Co.
Ames Metal Products Co.
Apex Rack and Coating Co.
Artcraft Welding Specialty Inc.
Associated Rack Corp.
AstroCosmos Metallurgical Inc.
Atotech USA Inc.
B&P Plating Supply, Div. of Behrens & Peatman LLC
Belke Mfg. Co.
Bison Corp.
Canfield Technologies Inc.
Chemtech Finishing Systems Inc.
Cooley Wire Products Mfgl. Co.
Division Lead Ltd. Partnership
Entone-OMI Inc.
HBS Equipment Corp.
Hardwood Line Mfg. Co.
Hydel Engineering Ltd.
Hyundai Titanium Co. Ltd.
Intrepid Industries Inc.
Mitchell-Bate Co.
National Rack Co.
New England Rack Co. Inc.
Pavco Inc.
Plastinetics Inc.
Plating Products Co. Inc.
Plating Products Inc.
Plating Supplies International Inc.
Reliable-West Tech Inc.
Republic Metal Inc.
SPF Corp. of America
Southeastern Rack Co.
Southwestern Rack Co.
Stutz Co.
Sweet Chemical Services Co. Inc.
Tilton Rack & Basket Corp.
Titan International Inc.
Titan Metal Fabricators Inc.
TriTech Technologies Inc.
Universal Rack Co.
Univertical Corp.
Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.

ANODE CLAMPS—See Anodizing, Clamps

ANODES, INSOLUBLE

Carbon and Graphite

Atotech USA Inc.
Becker Bros. Carbon Corp.
Plating Supplies International Inc.
Sifco Selective Plating, Div. of Sifco Industries Inc.
Technic Inc.
Unique Industries Inc.
Univertical Corp.

Ceramic and Metal Oxides

Ameritest and Research Co. Inc.
Eco-Tec Inc.
Eltech Systems Corp., Anode Technologies Group
Lambertville Ceramic Mfg. Co.
Technic Inc.

Lead

Alpha Metals Inc.
Ames Metal Products Co.
Atotech USA Inc.
Belmont Metals Inc.
Canfield Technologies Inc.
Chemtech Finishing Systems Inc.
Division Lead Ltd. Partnership
Engelhard Electro Metallics Div.
Hard Chrome Plating Consultants Ltd.
International Metals and Chemicals Group
JPS Technologies Inc.
New England Rack Co. Inc.
Redring Electric Co.
Republic Metal Inc.
Rin Inc.
SPF Corp. of America
Technic Inc.
Titan International Inc.
Univertical Corp.
Victory White Metal Co.

Platinum Clad

Chemtech Finishing Systems Inc.
De Nora America Inc.
Degussa Hüls Corp.

Electrode Products Inc.
Eltech Systems Corp., Anode Technologies Group
Engelhard Electro Metallics Div.
Entone-OMI Inc.
HBS Equipment Corp.
Intrepid Industries Inc.
Johnson Matthey Inc., Materials Technology Div.
King Corp., Larry
Liquid Development Co.
New England Rack Co. Inc.
SPF Corp. of America
Sifco Selective Plating, Div. of Sifco Industries Inc.
Smith Precious Metals Co.
Southern Industrial Chemicals Inc.
TDK Ohio Corp.
Technic Inc.
Uyemura Corp.
Vincent Metals Corp.

Steel and Stainless Steel

Chemtech Finishing Systems Inc.
Intrepid Industries Inc.
Liquid Development Co.
New England Rack Co. Inc.
Plating Supplies International Inc.
Sifco Selective Plating, Div. of Sifco Industries Inc.
Stutz Co.
Technic Inc.

ANODES, SOLUBLE

Brass and Bronze

Atlas Technicast Ltd.
Atotech USA Inc.
Belmont Metals Inc.
Chemtech Finishing Systems Inc.
HBS Equipment Corp.
International Metals and Chemicals Group
Technic Inc.
Titan International Inc.
Univertical Corp.
Western Reserve Mfg. Co. Inc.

Cadmium

AIM Products Inc.
Belmont Metals Inc.
Canfield Technologies Inc.
Chemtech Finishing Systems Inc.
Engelhard Electro Metallics Div.
International Metals and Chemicals Group
Kraft Chemical Co.
Pavco Inc.
Tally Metal Sales Inc.
Technic Inc.
Titan International Inc.
Univertical Corp.

Cobalt

International Metals and Chemicals Group
Technic Inc.
Univertical Corp.

Copper

Allied-Hunter Corp.
Associated Rack Corp.
Atlas Technicast Ltd.
Atotech USA Inc.
Belmont Metals Inc.
Canfield Technologies Inc.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemtech Finishing Systems Inc.
Electric Materials Co.
Engelhard Electro Metallics Div.
HBS Equipment Corp.
International Metals and Chemicals Group
Kraft Chemical Co.
Metallurgical Products Co.
Reliable-West Tech Inc.
Sherburne Metal Products Inc.
Southeastern Rack Co.
Tally Metal Sales Inc.
Technic Inc.
Titan International Inc.
Univertical Corp.
Western Reserve Mfg. Co. Inc.

Indium

Indium Corp. of America
Technic Inc.

Lead

Ames Metal Products Co.
Atotech USA Inc.
Belmont Metals Inc.
Chemtech Finishing Systems Inc.
Division Lead Ltd. Partnership

Nickel

Allied-Hunter Corp.
Atotech USA Inc.
Belmont Metals Inc.
Canfield Technologies Inc.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemtech Finishing Systems Inc.
Engelhard Electro Metallics Div.
Falconbridge U.S. Inc.
HBS Equipment Corp.
INCO Ltd.
International Metals and Chemicals Group
International Nickel Inc.
Kraft Chemical Co.
Pavco Inc.
Rin Inc.
Tally Metal Sales Inc.
Technic Inc.
Titan International Inc.
Univertical Corp.
Uyemura Corp.

Silver

AIM Products Inc.
Canfield Technologies Inc.
Chemtech Finishing Systems Inc.
Covofinish Co. Inc.
Engelhard Electro Metallics Div.
Entone-OMI Inc.
HBS Equipment Corp.
Handy & Harman, Industrial Products Group
International Metals and Chemicals Group
Meloon Enterprises Inc.
Reliable-West Tech Inc.
Smith Precious Metals Co.
Technic Inc.
Titan International Inc.
Univertical Corp.

Solder

AIM Products Inc.
Alpha Metals Inc.
Ames Metal Products Co.
Atotech USA Inc.
Belmont Metals Inc.
Canfield Technologies Inc.
Division Lead Ltd. Partnership
Indium Corp. of America
International Metals and Chemicals Group
Kraft Chemical Co.
Lucent Technologies
Redring Electric Co.
Reliable-West Tech Inc.
Technic Inc.
Titan International Inc.
Univertical Corp.
Victory White Metal Co.

Tin

AIM Products Inc.
Alpha Metals Inc.
Ames Metal Products Co.
Atotech USA Inc.
Belmont Metals Inc.
Canfield Technologies Inc.
Chemtech Finishing Systems Inc.
Division Lead Ltd. Partnership
HBS Equipment Corp.
International Metals and Chemicals Group
Kraft Chemical Co.
Redring Electric Co.
Reliable-West Tech Inc.
Tally Metal Sales Inc.
Technic Inc.
Titan International Inc.
Univertical Corp.
Victory White Metal Co.

Zinc

Belmont Metals Inc.
Canfield Technologies Inc.
Chemtech Finishing Systems Inc.
Electrode Products Inc.
Engelhard Electro Metallics Div.
HBS Equipment Corp.
Imperial Zinc Corp.
International Metals and Chemicals Group

Kraft Chemical Co.
Pavco Inc.
Tally Metal Sales Inc.
Technic Inc.
Titan International Inc.
Univertical Corp.

ANODIZING

(See also Plating and Anodizing Equipment and Racks for Plating and Anodizing)

Clamps

Anodic Inc.
AstroCosmos Metallurgical Inc.
Burlingham International
Chemtech Finishing Systems Inc.
Echo Supply
Leed Himmel
Mitchell-Bate Co.
Moldsaver Inc.
Sequel Corp.
Technic Inc.
Tilton Rack & Basket Corp.
TriTech Technologies Inc.
Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.

Dyes

Albright & Wilson Americas
Aldoa Co.
Chemtech Finishing Systems Inc.
Clariant Corp.
Goldschmidt Industrial Chemical Corp.
Henkel Surface Technologies
Houghton Metal Finishing Co.
Luster-On Products Inc.
MacDermid Inc.
Patrick & Co. Inc., C.H.
Pylam Products Co. Inc.
Southern Industrial Chemicals Inc.
Technic Inc.
U.S. Specialty Color Corp.

Processes

Albright & Wilson Americas
Brent America Inc.
Chemical Solvents Inc.
Chemtech Finishing Systems Inc.
Clariant Corp.
Coral Chemical Co.
Haviland Products Co.
Henkel Surface Technologies
Houghton Metal Finishing Co.
Iso-Cor Inc.
JacksonLea, A Unit of Jason Inc.
Liquid Development Co.
MacDermid Inc.
Metal Chem Inc.
METALAST International Inc.
Oakite Products Inc., A Member of The Chemetall Group
Okuno Chemical Industries Co. Ltd.
Oliver Sales Co.
Pilot Chemical Co.
Sanford Process Corp.
Sifco Selective Plating, Div. of Sifco Industries Inc.
Southern Industrial Chemicals Inc.
Stone Chemical Co.
Sur-Fin Chemical Corp.
Technic Inc.
Technology Applications Group Inc.
U.S. Specialty Color Corp.

Seals

Albright & Wilson Americas
BF Services
Benchmark Products Inc.
Chemtech Finishing Systems Inc.
Clariant Corp.
Enequist Chemical Co. Inc.
Goldschmidt Industrial Chemical Corp.
Henkel Surface Technologies
Houghton Metal Finishing Co.
Iso-Cor Inc.
JacksonLea, A Unit of Jason Inc.
Lockheed Aeronautical Systems Co.
MacDermid Inc.
Oakite Products Inc., A Member of The Chemetall Group
Okuno Chemical Industries Co. Ltd.
Oliver Sales Co.
Plating Resources Inc.
Stone Chemical Co.
Triple-S Chemical Products Inc.
U.S. Specialty Color Corp.

Titanium Racks

Able Rack Co.
Accurate Rack Co.
Associated Rack Corp.
AstroCosmos Metallurgical Inc.
Belke Mfg. Co.
Chemtech Finishing Systems Inc.
National Rack Co.
Sequel Corp.
Servi-Sure Corp.
Southeastern Rack Co.
Southwestern Rack Co.
TriTech Technologies Inc.
Universal Rack Co.
Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.

BACKSTAND IDLERS—See Belt Polishing

BARREL PLATING SUPPLIES

Danglers, Plated Copper Balls, Button Contacts

American Wire & Cathode Corp.
Atotech USA Inc
B&P Plating Supply, Div. of Behrens & Peatman LLC
Belke Mfg. Co.
Catho-Pin Products
Chemtech Finishing Systems Inc.
Danglers Inc.
Hardwood Line Mfg. Co.
Imperial Industries Inc.
Jessup Engineering Inc.
Napco Inc.
Newact Inc.
Plastic Methods Co.
Plating Products Co. Inc.
Plating Supplies International Inc.
Savitt Industrial Products Inc.
Singleton Corp.
Starline Products
Sterling Systems Sales Corp.
Stutz Co.
Technic Inc., Equipment Div.
TriTech Technologies Inc.

BARRELS, PLATING

American Plating Systems, Div. of Stewart Technologies Inc.
Atotech USA Inc.
B&P Plating Supply, Div. of Behrens & Peatman LLC
Baker Co., M.E.
Belke Mfg. Co.
Brian Co. Ltd., M.A.
Buchholz Smith Plastic Fabrication Inc.
Chemtech Finishing Systems Inc.
Coscina Associates Inc., Frank J.
Desco Inc.
ECI Technology Inc.
Entone-OMI Inc.
FPI Systems Inc.
GET Systems Inc.
Greco Bros. Inc.
HBS Equipment Corp.
Hardwood Line Mfg. Co.
Heatbath Corp.
Imperial Industries Inc.
Jessup Engineering Inc.
King Corp., Larry
Leatherwood Plastics, Div. of Leatherwood Inc.
Linnhoff Inc.
Luster-On Products Inc.
Manz Galvano-Technik GmbH
Mesa West Inc.
Mid-Western Processes Inc.
Napco Inc.
Oaks Industries Inc.
PAL Sales Inc.
Plasfab Inc.
Plating Products Co. Inc.
Richard Tscherwitschke GmbH, Kunststoff-Apparatebau und Ablufttechnik
Singleton Corp.
Starline Products
Sterling Systems Sales Corp.
Stutz Co.
Technic Inc., Equipment Div.

TriTech Technologies Inc.
Upton Industries Inc.
Whyco Technologies Inc.

BARRELS, TUMBLING—See Mass Finishing Equipment

BASKETS, DIPPING AND HANDLING
AB Plastics Inc.
Able Rack Co.
Accurate Rack Co.
Apex Rack and Coating Co.
Associated Rack Corp.
AstroCosmos Metallurgical Inc.
B&P Plating Supply, Div. of Behrens & Peatman LLC
BKTS Inc.
Belke Mfg. Co.
Cooley Wire Products Mfgl. Co.
Desco Inc.
Echo Supply
Heatbath Corp.
Ideal Rack Inc.
Imperial Industries Inc.
Jessup Engineering Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Liberty Machine Co. Inc.
Luster-On Products Inc.
Napco Inc.
National Rack Co.
New England Rack Co. Inc.
New Products Inc.
Oaks Industries Inc.
PKG Equipment Inc.
Patrick Co., P.N.
Philip Machine Co.
Plastinetics Inc.
Plating Products Co. Inc.
Plating Products Inc.
Plating Supplies International Inc.
Rack Processing Co.
Servi-Sure Corp.
Southeastern Rack Co.
Southwestern Rack Co.
Sterling Systems Sales Corp.
Technic Inc., Equipment Div.
Tilton Rack & Basket Corp.
Universal Rack Co.
Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.

BELT POLISHING

Backstand Idlers
Acme Mfg. Co.
Formax Mfg. Corp.
Grinding & Polishing Machinery Corp.
Hammond Machinery Inc.
Harper Surface Finishing Systems Inc.
Munson Machinery Co. Inc.
Nu-Matic Grinders Inc.
Reliable Equipment Corp.
Schaffner Mfg. Co. Inc.
Timesavers Inc.

Belts
Abrasive Service Co. Inc.
Acme Belt Recoating Inc.
American Siepmann
Belanger Inc.
Beltservice Corp.
Bison Corp.
Carborundum Abrasive Co.
Codman Co., F.L. & J.C.
Divine Brothers Co.
Duraline Abrasives Inc.
Formax Mfg. Corp.
Hermes Abrasives Ltd.
Iding Co. Inc., M.P.
Klingspor Abrasives Inc.
Matchless Metal Polish Co.
Merit Abrasive Products Inc.
Micro-Surface Finishing Products Inc.
Mitchell Co. Inc., E.C.
Norton Co.
Schaffner Mfg. Co. Inc.
Spartan Felt Co.
Stan Sax Corp.
3M Co., Abrasive Systems Div.
United Abrasive Inc.
VSM Abrasives Corp.
Van Industries Inc.
Vibra Finish Co.
Yerges Mfg. Co.

Contact Wheels
American Siepmann
Bison Corp.
Codman Co., F.L. & J.C.
Contact Rubber Corp.
Divine Brothers Co.
Dynabrade Inc.
Formax Mfg. Corp.
Graves Co.
Iding Co. Inc., M.P.
Matchless Metal Polish Co.
Nu-Matic Grinders Inc.
Olean Finishing Machine Co. Inc.
Pinnacle Technologies Inc.
RotaDyne, Engineered Roller Div.
Schaffner Mfg. Co. Inc.
Spartan Felt Co.
3M Co., Abrasive Systems Div.
Timesavers Inc.
Yerges Mfg. Co.

Lubricants
Bison Corp.
Divine Brothers Co.
Formax Mfg. Corp.
Iding Co. Inc., M.P.
International Chemical Co.
JacksonLea, A Unit of Jason Inc.
Matchless Metal Polish Co.
Schaffner Mfg. Co. Inc.
Stutz Co.
Van Industries Inc.

Machines
Abrasive Engineering & Mfg.
Acme Mfg. Co.
American Siepmann
Dynabrade Inc.
Hammond Machinery Inc.
Harper Surface Finishing Systems Inc.
Hill Acme Co.
Kalamazoo Industries
Munson Machinery Co. Inc.
Olean Finishing Machine Co. Inc.
Rand-Bright Corp.
Reliable Equipment Corp.
Schaffner Mfg. Co. Inc.
Timesavers Inc.
Westar Mfg. Corp.

BLACKENING AND ANTIQUING PROCESSES
A Brite Co.
Acme Metal Finishing Co. Inc.
Alchem Corp.
Aldoa Co.
Birchwood Laboratories Inc.
Bison Corp.
Chemtech Finishing Systems Inc.
Cleveland Black Oxide
Deveco Corp.
Du-Lite Corp.
EZE Products Inc.
Electrochemical Products Inc. (EPI)
Enequist Chemical Co. Inc.
Entone-OMI Inc.
Haviland Products Co.
Heatbath Corp.
Henkel Surface Technologies
Houghton International Inc.
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Kurts & Wolfe Chemical Co. Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Metal Chem Inc.
Mid-State Chemical & Supply Corp.
Oliver Sales Co.
Patclin Chemical Co. Inc.
Pavco Inc.
Pax Surface Chemicals Inc.
Plating Products Co. Inc.
Rin Inc.
Savitt Industrial Products Inc.
Special Chemicals Inc.
Specialty Chemical Industry Corp.
Sur-Fin Chemical Corp.
Technic Inc.
Tivian Industries Ltd.
Triple-S Chemical Products Inc.
Tronex Chemical Corp.
Working Solutions Inc.
Zinex Corp.

BLASTING EQUIPMENT

ABB Air Preheater Inc., Ehrsam Blast Systems
Aero-Blast Products Inc.
Applied Surface Technologies
Aubin Co., A.E.
Automation Products Inc.
BOC Gases
Blast-It-All
CAE Alpheus Inc.
Church & Dwight Co. Inc.
Clemco Industries Corp., Zero Products Div.
Comco Inc.
Composition Materials Co. Inc.
Electronics Inc.
Empire Abrasive Equipment Co.
Finishers Technology Corp.
Flow Systems Inc.
Goff Corp., Div. George Fischer Foundry Systems Inc.
Guyson Corp. of U.S.A.
Hunter Products Inc.
Jet Edge, A Div. of TC/American Monorail Inc.
Jet Wheelblast Equipment, Div. of B&U Corp.
Kleer-Flo Co.
Kleiber & Schulz Inc.
Kocour Co. Inc.
Kramer Industries Inc.
LS Industries
Lake Buchanan Industries Inc.
Liquid Development Co.
Maxi-Blast Inc.
Media Blast & Abrasives Inc.
Pangborn Corp.
Pauli Systems
Pressure Blast Mfg. Co. Inc.
Progressive Technologies
Raytech Industries, A Div. of Lyman Products Corp.
3R Mineral & Mfg. Co.
United Abrasive Inc.
Universal Equipment Mfg. Co. Inc.
USFilter/Wheelabrator
Vapor Blast Mfg. Co.
Vibra Finish Co.
Vibra Finish Ltd.
Viking Corp.
White Technologies Inc., S.S.

BLASTING MEDIA

Agricultural

Andersons
Composition Materials Co. Inc.
Green Products Co.
Guyson Corp. of U.S.A.
Jet Wheelblast Equipment, Div. of B&U Corp.
United Abrasive Inc.
Vibra Finish Co.

Ceramic

Church & Dwight Co. Inc.
Electro Abrasives Corp.
Exolon-ESK Co.
Guyson Corp. of U.S.A.
Malvern Minerals Co.
Micro-Surface Finishing Products Inc.
Norton Co.
SEPR Ceramic Beads & Powders
Treibacher Schleifmittel Corp.
United Abrasive Inc.
Vibra Finish Co.
Vibra Finish Ltd.
Washington Mills Electro Minerals

Glass Beads

Cataphote Co.
Composition Materials Co. Inc.
Flex-O-Lite Div.
Guyson Corp. of U.S.A.
Jaygo Inc.
Jet Wheelblast Equipment, Div. of B&U Corp.
K.C. Abrasive Co. Inc.
Potters Industries Inc., An Affiliate of the PQ Corp.
Sil-trade USA Inc.
United Abrasive Inc.
USFilter/Wheelabrator
Vibra Finish Co.
Vibra Finish Ltd.
White Technologies Inc., S.S.

Metallic

Abbott Ball Co.
Composition Materials Co. Inc.
Division Lead Ltd. Partnership
Gloerfeld Co., Hermann, Div. of Wheelabrator Allevard Ent. Co.
Guyson Corp. of U.S.A.
Jet Wheelblast Equipment, Div. of B&U Corp.
Maxi-Blast Inc.
PanAbrasive Inc.
Peerless Metal Powders & Abrasive
Platt Bros. & Co.
United Abrasive Inc.
U.S. Technology Corp.
Vibra Finish Ltd.
Vulkan Blast Shot Technology
Wheelabrator Abrasives Inc.

Plastic

AC Molding Compounds
Aero-Blast Products Inc.
Guyson Corp. of U.S.A.
Jet Wheelblast Equipment, Div. of B&U Corp.
Maxi-Blast Inc.
Patent Plastics Inc.
Potters Industries Inc., An Affiliate of the PQ Corp.
U.S. Chemical & Plastics Inc.
U.S. Technology Corp.

Sodium Bicarbonate

Church & Dwight Co. Inc.

BLOWERS, EXHAUST—See Ventilation Equipment

BLOWERS, SOLUTION AGITATION

Ametek Rotron
Jessup Engineering Inc.
SERFILCO Ltd.
TriTech Technologies Inc.

BRASS PLATING—See Plating Processes

BRIGHT DIPS—See Pickling and Bright Dipping Processes

BRIGHTENER FEEDERS—See

BRONZE PLATING—See Plating Processes

BRUSH PLATING PROCESSES AND EQUIPMENT

Ameracar Inc.
Automation Products Inc.
Brooktronics Engineering Corp.
Carolinch Co.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Degussa Hüls Corp.
Dynatronix Inc.
Entone-OMI Inc.
Environmental Plating Technology Inc.
Hunter Products Inc.
International Surface Technology Ltd.
Liquid Development Co.
Meco Equipment U.S.A. Inc.
METFAB Technologies Inc.
Shipley Ronal
Sifco Selective Plating, Div. of Sifco Industries Inc.
Technic Inc.
Vincent Metals Corp.
W.R. Associates Inc.

BRUSHES

Anderson Products Inc., Subsidiary of Wilton Corp.
CIMID
Divine Brothers Co.
DuPont Polymers, Filament Products
Felton Brush Inc.
Formax Mfg. Corp.
Gesswein & Co., Paul H.
Gordon Brush Mfg. Co. Inc.
Jenkins' Sons Inc., M.W.
Johnson Brush Co.
Milwaukee Brush Mfg. Co.
Osborn International, A Unit of Jason Inc.
3M Co., Abrasive Systems Div.
United Abrasive Inc.

Weiler Corp.

BUFF RAKES
Formax Mfg. Corp.
JacksonLea, A Unit of Jason Inc.
Manderscheid Equipment & Supply
Schaffner Mfg. Co. Inc.

BUFFING COMPOUND APPLICATORS
American Siepmann
Bison Corp.
Formax Mfg. Corp.
Harper Surface Finishing Systems Inc.
JacksonLea, A Unit of Jason Inc.
Okuno Chemical Industries Co. Ltd.
Olean Finishing Machine Co. Inc.
Paasche Airbrush Co.
Schaffner Mfg. Co. Inc.
Spartan Felt Co.
Stan Sax Corp.
U.S. Chemical & Plastics Inc.

BUFFING COMPOUNDS

Bar and Liquid
Acme Metal Finishing Co. Inc.
Aldoa Co.
Bison Corp.
CIMID
Competition Chemicals Inc.
Divine Brothers Co.
Formax Mfg. Corp.
Graves Co.
Iding Co. Inc., M.P.
JacksonLea, A Unit of Jason Inc.
Jescar Enterprises Inc.
Kocour Co. Inc.
MacDermid Inc.
Matchless Metal Polish Co.
Mosher Co. Inc.
Okuno Chemical Industries Co. Ltd.
Schaffner Mfg. Co. Inc.
Sintex Minerals Services Inc.
Spartan Felt Co.
Stan Sax Corp.
Stutz Co.
Uyemura Corp.
Van Industries Inc.
Yerges Mfg. Co.

BUFFING EQUIPMENT—See Polishing and Buffing Equipment

BUFFS
Bison Corp.
CIMID
CS Unitec
Codman Co., F.L. & J.C.
Divine Brothers Co.
Formax Mfg. Corp.
Graves Co.
Harper Surface Finishing Systems Inc.
JacksonLea, A Unit of Jason Inc.
Lake Country Mfg. Inc.
Matchless Metal Polish Co.
Osborn International, A Unit of Jason Inc.
Reliable Buff Co.
Schaffner Mfg. Co. Inc.
Sintex Minerals Services Inc.
Spartan Felt Co.
Stan Sax Corp.
Van Industries Inc.
Vibra Finish Co.
Williamsville Buff Co.
Yerges Mfg. Co.

BURNERS—See Heaters and Heat Transfer Equipment

BURNISHING MEDIA—See Mass Finishing Supplies

BUS BAR SYSTEMS
Anomet Products Inc.
Automate Tech Inc.
Belke Mfg. Co.
Dynapower Corp.
Electric Materials Co.
Leatherwood Plastics, Div. of Leatherwood Inc.
Mitchell-Bate Co.
SPF Corp. of America
Technic Inc., Equipment Div.

CADMIUM PLATING—See Plating Processes

CAPS AND PLUGS—See Masking, Caps and Plugs

CARBONATE REMOVAL SYSTEMS
Armstrong Engineering Associates Inc.
USFilter/JWI

CEMENT, ACIDPROOF
Advanced Materials Inc.
Atlas Minerals & Chemicals Inc.
Ceilcote Air Pollution Control
Dudick Corrosion Proof Inc.
Elf Atochem North America Inc.

CENTRIFUGAL DRYERS—See Drying Equipment

CENTRIFUGES—See Sludge Handling Equipment

CHEMICAL FEEDERS
American Plating Systems, Div. of Stewart Technologies Inc.
Aqualogic Inc.
Atotech USA Inc.
Bran + Luebbe
Capital Controls Co. Inc.
Duriron Co. Inc., Engineered Systems Group
Entone-OMI Inc.
HBS Equipment Corp.
Hoffland Environmental Inc.
Hoover Container Sales & Service Inc., Subsidiary of Hoover Group Inc.
Ivek Corp.
Iwaki Walchem Corp.
Komax Systems Inc.
Kontek Ecology Systems Inc.
LMI, Div. of Milton Roy
MacDermid Inc.
McGean-Rohco Inc.
Mesa West Inc.
Neptune Chemical Pump Co.
North American Rectifier Ltd.
Osmonics/Autotrol
Parker Systems, Div. of D.J. Parker Co.
Process Electronics Corp.
ProMinent Fluid Controls Inc.
SERFILCO Ltd.
Starlite Technical Service Inc.
Systematics Inc.
Technic Inc., Equipment Div.
Trilectron Industries Inc.
TriTech Technologies Inc.
Vanton Pump & Equipment Corp.
Walchem Corp.
Walgren Co.

CHILLERS
API Heat Transfer Inc.
Applied Thermal Technologies Inc., Hydro-Miser Div.
Armstrong Engineering Associates Inc.
Calfran International Inc.
Cooling Technology Inc.
FlatPlate Inc.
Process Chiller Systems Inc.
SPF Corp. of America
Technic Inc., Equipment Div.
Tek-Temp Inc.
Tranter Inc.
TriTech Technologies Inc.
Zarsky Industries

CHLORINATORS—See Water Pollution Control Processes and Equipment

CHROMATE COATINGS—See Conversion Coating Processes

CHROMIUM PLATING—See Plating Processes

CLARIFIERS—See Water Pollution Control Processes and Equipment

CLEANER RECYCLING SYSTEMS

ACG Technology Ltd.
Alfa Laval Separation Inc.
Aqueous Recovery Resources Inc.
Durr Ecoclean
Environmental Water Engineering
Graver Technologies Inc.
Graymills Corp.
Hyde Products Inc.
IEECO Inc.
Infinitex
Kleer-Flo Co.
L&R Mfg. Co.
L&T Technologies Inc.
METFAB Technologies Inc.
Midbrook Inc.
Pavco Inc.
R-V Industries Inc.
Sanborn Technologies, A Waterlink Co.
Separation Dynamics Inc.
Separation Technologists Inc.
Seprotech Systems Inc.
SystemOne Technologies Inc.
Treatment Products Corp.

CLEANERS, ALKALINE, ACIDIC, AND EMULSION

A Brite Co.
ACI Chemicals Inc.
Abatement Technologies
Accurate Engineering Labs, Div. of Rin Inc.
Acme Metal Finishing Co. Inc.
Aerocote Corp.
Albright & Wilson Americas
Alchem Corp.
Alconox Inc.
Aldoa Co.
American Chemical & Equipment
American Chemical Products Corp.
Arconium
Atotech USA Inc.
BF Services
Benchmark Inc.
Benchmark Products Inc.
BetzDearborn, Div. of Hercules Inc.
BioClean USA
Birchwood Laboratories Inc.
Bison Corp.
Brent America Inc.
Broco Products Inc.
Brulin Corp.
Calgon Corp.
Castrol Industrial North America
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemtech Finishing Systems Inc.
Church & Dwight Co. Inc.
Circle-Prosco Inc.
Clariant Corp.
Competition Chemicals Inc.
Coral Chemical Co.
Crest Ultrasonics Corp.
Delta Foremost Chemical Corp.
Detrex Corp., Solvents and Environmental Services Div.
Deveco Corp.
Dow Chemical Co.
DuBois, Div. of Diversey Lever
DuPont Co.
EZE Products Inc.
Electrochemical Products Inc. (EPI)
Elf Atochem North America Inc.
Enequist Chemical Co. Inc.
Entone-OMI Inc.
Etus Inc.
Fremont Industries Inc.
Grace & Co., W.R.
Graymills Corp.
Haviland Products Co.
Heatbath Corp.
Henkel Surface Technologies
Houghton Metal Finishing Co.
Hubard-Hall Inc.
International Chemical Co.
International Products Corp.
JacksonLea, A Unit of Jason Inc.
Kraft Chemical Co.
Kurts & Wolfe Chemical Co. Inc.
Kyzen Corp.
L&R Mfg. Co.
Luster-On Products Inc.
MacDermid Inc.
Magnuson Product Corp.
Markee Corp.
McGean-Rohco Inc.
Metal Chem Inc.
Metal Coatings International Inc.
Metalline Corp.
Mid-State Chemical & Supply Corp.
Midbrook Inc.
Missouri Electrochem Inc.
Modern Chemical Inc.
Morton Electronic Materials, Morton International Inc.
Nalco Chemical Co.
Navy Brand Mfg. Co.
New Surface Technologies
OMG Fidelity
Oakite Products Inc., A Member of The Chemetall Group
Okuno Chemical Industries Co. Ltd.
Oliver Sales Co.
PCI of America
PCT Technology Inc.
PPG Pretreatment & Specialty Products
Patclin Chemical Co. Inc.
Pavco Inc.
Pax Surface Chemicals Inc.
Prosco Inc.
Quaker Chemical Corp.
REM Chemicals Inc.
Rin Inc.
Rochester Midland Corp.
Shipley Ronal
Sonicor Instrument Corp.
Southern Industrial Chemicals Inc.
Stapleton Technologies
Starlite Technical Service Inc.
Stellar Solutions Inc.
Stone Chemical Co.
Straus Chemical Corp.
Sur-Fin Chemical Corp.
Taskem Inc.
Technic Inc.
Terpene Technologies Inc.
Texo Corp.
Thermo-Cote Inc.
Tivian Industries Ltd.
Todco Industries Inc.
Tower Chemical Corp.
Tronex Chemical Corp.
Tru-Chem Co. Inc.
U.C.R. Inc.
U.S. Specialty Color Corp.
Uyemura Corp.
WSI Chemical Inc.
Working Solutions Inc.

CLEANERS, SOLVENT

Aerocote Corp.
Albemarle Corp.
AlliedSignal Inc., Fluorine Products
Amity Ltd.
BASF Corp., Chemicals Div.
BioChem Systems
Chemtech Finishing Systems Inc.
Chemtronics
Crest Ultrasonics Corp.
Detrex Corp., Solvents and Environmental Services Div.
Dow Corning Corp.
DuPont, Fluoro Polymers Div.
Dynamold Solvents Inc.
Ecolink Inc.
Enviro Tech International Inc.
Exxon Chemical Co.
Graymills Corp.
Kyzen Corp.
LPS Laboratories Inc.
MacDermid Inc.
Mid-State Chemical & Supply Corp.
Navy Brand Mfg. Co.
Penetone Corp.
Petroferm Inc.
Working Solutions Inc.
WSI Chemical Inc.

CLEANING EQUIPMENT—See Degreasers, Parts

Washers, and Ultrasonic Cleaning Equipment

COILS, HEATING AND COOLING—See Heaters and Heat Transfer Equipment

COLORING PROCESSES—See Blackening and Antiquing Processes

COMPRESSED AIR DRYERS AND FILTERS

AirCel Corp.
Deltech Engineering Inc.
Kaeser Compressors Inc.
La-Man Corp.
Van Air Systems Inc.
Zeks Air Drier Corp.

CONDUCTIVE PAINT

BFGoodrich Co., Corzan Industrial Systems Div.
Hommel Co., O.
Technic Inc.

CONDUCTIVITY CONTROLS

American Plating Systems, Div. of Stewart Technologies Inc.
Capital Controls Co. Inc.
DMP Corp.
Ecowater Industrial Systems
Fischer Technology Inc.
GLI International Inc.
George Fischer Inc.
Hach Co.
Industrial Instruments Inc.
Kontek Ecology Systems Inc.
LMI, Div. of Milton Roy
LaMotte Co.
Leeds & Northrup, A Unit of General Signal
McNab Inc.
Myron L Co.
PPG Pretreatment & Specialty Products
Palm Commodities International Inc.
ProMinent Fluid Controls Inc.
Rosemount Analytical, Uniloc Div.
Systematics Inc.
Technic Inc., Equipment Div.
TriTech Technologies Inc.
Walchem Corp.

CONSULTANTS

Anachem Laboratories
Applied Technical Services Inc.
Ashley Labs
Burns & McDonnell
CH2M Hill
Capaccio Environmental Engineering Inc.
Clayton Environmental Consultants Inc.
Covo Corp.
Davidoff, Charles
Donaldson, John G.
Finishing Technology
Hard Chrome Plating Consultants Ltd.
Horner, J.D.
Kushner Electroplating School
Lockwood Greene Engineers Inc.
Mabbett & Associates Inc.
Mandich, Ned V.
Monitor Consultants LLC
Platers Technical Service Inc.
Scientific Control Laboratories Inc.
TriTech Technologies Inc.
Wasserman, Arthur
Weiner, Milton
White Laboratory & Co., J.

CONTACT WHEELS—See Belt Polishing

CONVERSION COATING PROCESSES

(See also Blackening and Antiquing Processes and Phosphate Coating Processes)

Aluminum

A Brite Co.
ACI Chemicals Inc.
Aerocote Corp.
Alchem Corp.
Aldoa Co.
American Chemical & Equipment
Arcal Chemicals Inc.
BetzDearborn, Div. of Hercules Inc.
Birchwood Laboratories Inc.
Brent America Inc.
Chemat Technology Inc.
Chemtech Finishing Systems Inc.
Circle-Prosco Inc.
Coral Chemical Co.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Haviland Products Co.
Heatbath Corp.
Henkel Surface Technologies
Houghton Metal Finishing Co
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Missouri Electrochem Inc.
Natural Coating Systems LLC
Oakite Products Inc., A Member of The Chemetall Group
PPG Pretreatment & Specialty Products
Pavco Inc.
Pax Surface Chemicals Inc.
Sanchem Inc.
Southern Industrial Chemicals Inc.
Sur-Fin Chemical Corp.
Taskem Inc.
Texo Corp.
Triple-S Chemical Products Inc.
U.S. Specialty Color Corp.
Working Solutions Inc.

Cadmium

Alchem Corp.
Aldoa Co.
American Chemical & Equipment
Chemtech Finishing Systems Inc.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Entone-OMI Inc.
Heatbath Corp.
Henkel Surface Technologies
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Missouri Electrochem Inc.
PPG Pretreatment & Specialty Products
Pavco Inc.
Pax Surface Chemicals Inc.
Triple-S Chemical Products Inc.
U.C.R. Inc.

Copper

Aldoa Co.
Birchwood Laboratories Inc.
Chemtech Finishing Systems Inc.
Deveco Corp.
Heatbath Corp.
JacksonLea, A Unit of Jason Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Taskem Inc.
Triple-S Chemical Products Inc.

Magnesium

Chemtech Finishing Systems Inc.
Deveco Corp.
Heatbath Corp.
MacDermid Inc.
PPG Pretreatment & Specialty Products
Pax Surface Chemicals Inc.
Working Solutions Inc.

Silver

Aldoa Co.
Deveco Corp.
Heatbath Corp.
Luster-On Products Inc.
MacDermid Inc.
Patclin Chemical Co. Inc.
Pax Surface Chemicals Inc.
Triple-S Chemical Products Inc.

Zinc

A Brite Co.
ACI Chemicals Inc.
Accurate Engineering Labs, Div. of Rin Inc.
Acme Metal Finishing Co. Inc.
Aerocote Corp.
Alchem Corp.
Aldoa Co.
American Chemical & Equipment
Arconium
BASF Corp., Chemicals Div.
BetzDearborn, Div. of Hercules Inc.
Birchwood Laboratories Inc.
Chemtech Finishing Systems Inc.
Columbia Chemical Corp.
Continental Surface Treatment Inc.
Coral Chemical Co.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Entone-OMI Inc.
Heatbath Corp.
Henkel Surface Technologies
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Mid-State Chemical & Supply Corp.
Missouri Electrochem Inc.
Oakite Products Inc., A Member of The Chemetall Group
Okuno Chemical Industries Co. Ltd.
PPG Pretreatment & Specialty Products
Pavco Inc.
Pax Surface Chemicals Inc.
Rin Inc.
Shipley Ronal
Taskem Inc.
Texo Corp.
Triple-S Chemical Products Inc.
U.C.R. Inc.
Uyemura Corp.
Working Solutions Inc.

CONVEYORS

Allied UniKing Corp. Inc.
CAE Cleaning Technologies
KCH Services Inc., Engineered Services Div.
Midbrook Inc.
Technic Inc., Equipment Div.
Upton Industries Inc.

COOLING EQUIPMENT—See Chillers

COPPER PLATING—See Plating Processes and Electroless Plating Processes

CYCLONES—See Air Pollution Control Equipment

DANGLERS—See Barrel Plating Supplies

DEGREASERS, SOLVENT IMMERSION

Environmental Solvents Corp.

DEGREASERS, SOLVENT VAPOR

Baron Blakeslee Inc.
Branson Ultrasonics Corp.
Corpane Industries Inc.
Crest Ultrasonics Corp.
Detrex Corp., Equipment Div.
Durr Ecoclean
Finishing Equipment Inc.
Forward Technology Industries Inc.
Greco Bros. Inc.
K and M Electronics Inc.
Ramco Equipment Corp.
Rosemont Analytical
S&K Products International
Serec Corp.
Sonicor Instrument Corp.
Technic Inc., Equipment Div.
Ultra-Kool Inc.
Unique Industries Inc.
Vapor Engineering Inc.
Western Sonics

DEGREASERS, VACUUM

Ipsen International Inc.
Serec Corp.

DEIONIZERS

Bio-Recovery Systems Inc.
Ecowater Industrial Systems
Graver Water Systems Inc., Div. of Graver Co.
Ion Exchange Products Inc.
Ionics Inc., Separations Technology Div.
Kinetico Inc., Engineered Systems Div.
Koch Membrane Systems Inc.
Master Process Systems Inc.
Osmonics Inc.
Penfield Liquid Treatment Systems
Technic Inc., Equipment Div.
Treatment Products Corp.
TriTech Technologies Inc.
USFilter/Ionpure

DESCALERS—See Pickling and Bright Dipping Processes

DIALYSIS EQUIPMENT—See Waste Recovery Processes and Equipment

DRUM PUMPS—See Pumps

DRY FILM LUBRICANTS

Dixon Ticonderoga Co.
Dow Corning Corp.
E/M Engineered Coating Solutions
KHI Coating
Mid-State Chemical & Supply Corp.
Orpac Inc.
Tronex Chemical Corp.
Trutec Industries
Whitford Corp.

DRYING EQUIPMENT

Centrifugal

Atotech USA Inc.
Barrett Centrifugals Inc.
Desco Inc.
Finishing Equipment Inc.
Greco Bros. Inc.
HBS Equipment Corp.
Leatherwood Plastics, Div. of Leatherwood Inc.
Linnhoff Inc.
New Holland North America Inc.
Nobles Mfg. Inc.
Oaks Industries Inc.
Plating Products Co. Inc.
Plating Supplies International Inc.
Singleton Corp.
Technic Inc., Equipment Div.
Triad Industries Inc.
TriTech Technologies Inc.

Cob Meal Reclaiming

C&S Engineering Corp.
Delrod Sales Corp.
Rosemont Industries Inc.
Ultramatic Equipment Co.

Drum and Rotary

Acme-Fab, Div. AF Industries
Almco Inc.
C&S Engineering Corp.
Duriron Co. Inc., Engineered Systems Group
Harper Surface Finishing Systems Inc.
Imperial Industries Inc.
Jensen Fabricating Engineers Inc.
Midbrook Inc.
Napco Inc.
Technic Inc., Equipment Div.
TriTech Technologies Inc.

Vacuum

Altos Engineering Inc.

DRYING MATERIALS

Cob Meal and Sawdust
Greco Bros. Inc.

Drying Aids
Chemtech Finishing Systems Inc.
Haviland Products Co.
Hubard-Hall Inc.
Pavco Inc.
Plating Resources Inc.
Starlite Technical Service Inc.

DUCTS—See Ventilation Equipment

DUST COLLECTORS—See Air Pollution Control Equipment

DYES—See Anodizing

ELECTRIC HEATERS—See Heaters and Heat Transfer Equipment

ELECTRICAL METERING EQUIPMENT
Atotech USA Inc.
DMP Corp.
Dynapower Corp.
Dynatronix Inc.
Entone-OMI Inc.
HBS Equipment Corp.
JP Tech
Mesa West Inc.
North American Rectifier Ltd.
PDI Inc.
PWR Inc.
Power Conversion Corp.
Process Technology Inc.
Rapid Power Technologies Inc.
SERFILCO Ltd.
Systematics Inc.
Technic Inc., Equipment Div.
Trilectron Industries Inc.
TriTech Technologies Inc.

ELECTRODEPOSITION OF METALS—See Plating Processes

ELECTRODIALYSIS EQUIPMENT—See Waste Recovery Processes and Equipment

ELECTROLESS PLATING PROCESSES

Copper
Atotech USA Inc.
Bison Corp.
Chemtech Finishing Systems Inc.
Deveco Corp.
Electrochemicals
Entone-OMI Inc.
Hubard-Hall Inc.
Luster-On Products Inc.
MacDermid Inc.
Morton Electronic Materials, Morton International Inc.
OMG Fidelity
Okuno Chemical Industries Co. Ltd.
Schlotter, Dr. Ing. Max
Seleco Inc.
Shipley Ronal
Surface Technology Inc.
Technic Inc.
Transene Co. Inc.
TriTech Technologies Inc.

Gold
Covofinish Co. Inc.
Entone-OMI Inc.
Okuno Chemical Industries Co. Ltd.
Shipley Ronal
Stapleton Technologies
Technic Inc.
Tivian Industries Ltd.
Uyemura Corp.

Nickel
Accurate Engineering Labs, Div. of Rin Inc.
Aldoa Co.
Atotech USA Inc.
Benchmark Products Inc.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemtech Finishing Systems Inc.
Deveco Corp.
Entone-OMI Inc.
Heatbath Corp.
Henkel Surface Technologies
Hesse & Cie., Dr.
Hubard-Hall Inc.
LeKem Inc.
MacDermid Inc.
McGean-Rohco Inc.
Metal Chem Inc.
OMG Fidelity
Occidental Chemical Corp.
Okuno Chemical Industries Co. Ltd.
Palm Commodities International Inc.
Pax Surface Chemicals Inc.
Plasfab Inc.
Plating Process Systems Inc.
Rhone-Poulenc Basic Chemicals Co.
Roberts Chemicals Co. Inc.
Seleco Inc.
Shipley Ronal
Sirius Technology Inc.
Stapleton Technologies
Surface Technology Inc.
Taskem Inc.
Technic Inc.
Transene Co. Inc.
U.C.R. Inc.
Uyemura Corp.
Wear-Cote International Inc.

Palladium
Callery Chemical Co.
Shipley Ronal
Technic Inc.

Silver
Jema-American Inc.
Peacock Laboratories Inc.
Shipley Ronal
Technic Inc.
Transene Co. Inc.

Tin
Atotech USA Inc.
Chemtech Finishing Systems Inc.
Deveco Corp.
Enequist Chemical Co. Inc.
MacDermid Inc.
McGean-Rohco Inc.
OMG Fidelity
Okuno Chemical Industries Co. Ltd.
Shipley Ronal
Technic Inc.
Tivian Industries Ltd.
Transene Co. Inc.
Uyemura Corp.

ELECTROLYTIC RECOVERY EQUIPMENT—See Waste Recovery Processes and Equipment

ELECTROPHORETIC COATINGS
Atotech USA Inc.
Chemtech Finishing Systems Inc.
Clearclad Coatings Inc.
Entone-OMI Inc.
MacDermid Inc.
Uyemura Corp.

ELECTROPLATING EQUIPMENT—See Plating and Anodizing Equipment

ELECTROPLATING PROCESSES—See Plating Processes

ELECTROPOLISHING

Electrolytes
Albright & Wilson Americas

Chemtech Finishing Systems Inc.
Dynetics Corp.
Electro Polish Systems Inc.
Electro-Glo Distribution Inc.
Enequist Chemical Co. Inc.
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Kurts & Wolfe Chemical Co. Inc.
MacDermid Inc.
McGean-Rohco Inc.
Metal Chem Inc.
Metal Coating Process Corp.
Molectrics Inc.
Pro Ep
Tivian Industries Ltd.
Working Solutions Inc.

Equipment

American Plating Systems, Div. of Stewart Technologies Inc.
Chemtech Finishing Systems Inc.
Electro Polish Systems Inc.
Electro-Glo Distribution Inc.
HBS Equipment Corp.
Metal Coating Process Corp.
Molectrics Inc.
Pro Ep
Technic Inc., Equipment Div.

EMULSION CLEANERS—See Cleaners, Alkaline, Acidic, and Emulsion

ETCHANTS

Aluminum

A Brite Co.
ACI Chemicals Inc.
Atotech USA Inc.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemtech Finishing Systems Inc.
DuBois, Div. of Diversey Lever
EZE Products Inc.
Electrochemical Products Inc. (EPI)
Henkel Surface Technologies
Houghton Metal Finishing Co.
Missouri Electrochem Inc.
Stone Chemical Co.
Triple-S Chemical Products Inc.
U.S. Specialty Color Corp.
Working Solutions Inc.

Copper

Chemtech Finishing Systems Inc.
McGean-Rohco Inc.
Technic Inc.
Triple-S Chemical Products Inc.

ETCHING MACHINES

Chemcut Equipment Group, Atotech USA Inc.
Circuit Chemistry Equipment
HBS Equipment Corp.
Leatherwood Plastics, Div. of Leatherwood Inc.
METFAB Technologies Inc.
Morton Electronic Materials, Morton International Inc.
Technic Inc., Equipment Div.
USFilter/Wheelabrator
White Technologies Inc., S.S.

EVAPORATORS—See Waste Recovery Processes and Equipment

EXHAUST SYSTEMS—See Ventilation Equipment

FILTER MEDIA

Albax Inc.
Ametek, Plymouth Products Div.
Andreae Filter
Asahi/America Inc.
Benchmark Products Inc.
Camac Industries
Complete Filtration
Contaminant Recovery Systems Inc.
Corode B.V.
Eimco Process Equipment Co.
Elf Atochem North America Inc.
Fiber Bond Corp.
Filter Pump Industries, Div. of Penguin Pumps Inc.
Filter Specialists Inc.
FilterCor Inc.
Filtration Products Ltd.
Flo King Filter Systems, Custom Masters Inc.
Goodman & Co. Inc., C.
Graver Technologies Inc.
Harmsco Industrial Filters
Hendor-PE Inc.
Hyde Products Inc.
Industrial Filter & Pump Mfg. Co.
Ionics Inc., Separations Technology Div.
Keystone Filter Div., Met-Pro Corp.
Lenser Filter Media
Mefiag Div., Met-Pro Corp.
Met-Chem Inc.
Oberlin Filter Co.
Osmonics Inc.
Pall Corp., Industrial Process Group
Plating Supplies International Inc.
Precise Filtration Products Inc.
SERFILCO Ltd.
Sethco Div., Met-Pro Corp.
Siebec
Sperry & Co., D.R.
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
UF Strainrite
USFilter/Filterite

FILTER PRESSES—See Sludge Handling Equipment

FILTRATION EQUIPMENT

Advanced Chemical Systems Inc.
Almco Inc.
Anode Products Co. Inc.
Aprochim USA Inc.
Asahi/America Inc.
Atlantech **Process Technology Inc.**
Automate Tech Inc.
Automation Products Inc.
Beaver Industries Inc.
Camac Industries
Chemtech Finishing Systems Inc.
Circuit Chemistry Equipment
Contaminant Recovery Systems Inc.
Corode B.V.
Duriron Co. Inc., Engineered Systems Group
Entone-OMI Inc.
Environmental Control Systems Inc.
Excel Plating Technology Inc.
Filter Pump Industries, Div. of Penguin Pumps Inc.
Filter Specialists Inc.
FilterCor Inc.
Filtration Group - Fluid Systems
Flo King Filter Systems, Custom Masters Inc.
Graver Technologies Inc.
Great Lakes Filter
Harmsco Industrial Filters
Harrington Industrial Plastics Inc.
Hendor-PE Inc.
Hoffland Environmental Inc.
Industrial Filter & Pump Mfg. Co.
Industrial Filters Co.
Komline-Sanderson Engineering Corp.
L.C. Fabricators Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Lufran Inc.
Mefiag Div., Met-Pro Corp.
Met-Chem Inc.
METFAB Technologies Inc.
Napco Inc.
Netzsch Inc.
Oberlin Filter Co.
Osmonics Inc.
PPG Pretreatment & Specialty Products
Pall Corp., Industrial Process Group
Palm Commodities International Inc.
Pavco Inc.
Penfield Liquid Treatment Systems
Plasmag Pump Co., Div. of Murdock Co.
Plating Resources Inc.
Plating Supplies International Inc.
Pollution Application Systems Co. Inc.
Prosys Corp.
Roilgard Inc.
Ronningen-Petter
SERFILCO Ltd.

Sethco Div., Met-Pro Corp.
Siebec
Sperry & Co., D.R.
Summit Scientific Corp.
Sweet Chemical Services Co. Inc.
Tarus Equipment Co.
Technic Inc., Equipment Div.
Total Filter Technology Inc.
Trionetics Inc.
TriTech Technologies Inc.
USFilter/IWT
Vanton Pump & Equipment Corp.
Walrus Pump & Filtration LLC
Warrender Ltd.

FLAP WHEELS

Anderson Products Inc., Subsidiary of Wilton Corp.
Belanger Inc.
Bison Corp.
CS Unitec
Divine Brothers Co.
Even Cut Abrasive Co.
Felton Brush Inc.
Formax Mfg. Corp.
Grinding & Polishing Machinery Corp.
Iding Co. Inc., M.P.
JacksonLea, A Unit of Jason Inc.
Klingspor Abrasives Inc.
Merit Abrasive Products Inc.
Norton Co.
Pferd Inc.
Schaffner Mfg. Co. Inc.
Spartan Felt Co.
Stan Sax Corp.
Standard Abrasives Inc.
3M Co., Abrasive Systems Div.
Weiler Corp.
Yerges Mfg. Co.

FLOCCULANTS—See Water Pollution Control Processes and Equipment

FLOORS AND DRAINS

ACO Polymer Products Inc.
Advanced Materials Inc.
Atlas Minerals & Chemicals Inc.
Ceilcote Air Pollution Control
Composite Structures International. Inc. (CSI)
Corrosion Technology Inc.
Dri-Dek Corp.
Dudick Corrosion Proof Inc.
Horton Materials & Engineering Inc.
Koch Engineering Co. Inc.
Master Builders Inc., Poly Floors and Coatings Div.
McNichols Co.
Morrison Molded Fiber Glass Co.
Prolite Plastics Ltd.
Protech Floorings & Linings Inc.
Seasafe Inc.
Technic Inc., Equipment Div.
Tepromark International Inc.

FUME SCRUBBERS—See Air Pollution Control Equipment

FUME SUPPRESSANTS

Chemical

Accurate Engineering Labs, Div. of Rin Inc.
Atotech USA Inc.
Belke Mfg. Co.
Bison Corp.
Chemtech Finishing Systems Inc.
Clariant Corp.
Dow Corning Corp.
Fremont Industries Inc.
Henkel Surface Technologies
JacksonLea, A Unit of Jason Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Pavco Inc.
Pax Surface Chemicals Inc.
Plating Resources Inc.

Floats, Plastic

Nalge Co.
Plating Products Co. Inc.
Savitt Industrial Products Inc.
Southwest United Industries Inc.
Techne Inc.

GLASS BEADS—See Blasting Media

GLOVES—See Safety Equipment

GOLD PLATING—See Plating Processes and Electroless Plating Processes

GRATINGS—See Floors and Drains

GRIT BLASTING—See Blasting

HARD COAT ANODIZING—See Anodizing

HEATERS AND HEAT TRANSFER EQUIPMENT

Coils and Plates

Alfa Laval Thermal Inc.
Ames Metal Products Co.
Ametek, Chemical Products Div.
AstroCosmos Metallurgical Inc.
Braude (London) Ltd., E.
Chemtech Finishing Systems Inc.
Chromalox
DEC International, Engineered Products Group
Division Lead Ltd. Partnership
Excel Plating Technology Inc.
Fluorotherm Polymers Inc.
George Fischer Inc.
Hyundai Titanium Co. Ltd.
Lufran Inc.
MBA Mfg. & Supply Co.
Mueller Co., Paul
Norton Performance Plastics Corp.
Plating Products Inc.
Plating Supplies International Inc.
Process Technology Inc.
Solvay Interox Inc.
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
Titan Metal Fabricators Inc.
Tranter Inc.
Vulcanium Plating Systems, Div. of Industrial Titanium Corp.
Walgren Co.

Drum Warmers

Chromalox
Plating Supplies International Inc.
Trueheat Corp.

Electric Immersion

Braude (London) Ltd., E.
Chemtech Finishing Systems Inc.
Chromalox
Cleveland Process Corp.
Excel Plating Technology Inc.
Glo-Quartz Electric Heater Co. Inc.
Heat Transfer Technology Inc.
Lufran Inc.
Plating Products Inc.
Plating Supplies International Inc.
Process Technology Inc.
Proheatco Mfg. Co.
Protherm Mfg. Co.
SPF Corp. of America
SERFILCO Ltd.
Sethco Div., Met-Pro Corp.
Technic Inc., Equipment Div.
Thermco Electric
TriTech Technologies Inc.
Trueheat Corp.
Walgren Co.
Wellman Thermal Systems Corp.

Gas Burners

Cleveland Process Corp.
Eclipse Combustion Inc.
Hones Inc., Charles A.
Indesco Products Inc.
North American Mfg. Co.
Power Flame Inc.
Walgren Co.

Heat Exchangers

API Heat Transfer Inc.
Ametek, Chemical Products Div.
Applied Thermal Technologies Inc., Hydro-Miser Div.
Armstrong Engineering Associates Inc.
AstroCosmos Metallurgical Inc.
Camac Industries
Corning Inc.
Eclipse Combustion Inc.
Epcon Industrial Systems Inc.
Fluidix Inc.
Fluorotherm Polymers Inc.
George Fischer Inc.
Hydro Dynamics Inc.
Industrial Filter & Pump Mfg. Co.
MacDermid Inc.
Mueller Co., Paul
Norton Performance Plastics Corp.
Pick Heaters Inc.
Process Technology Inc.
SPF Corp. of America
Tranter Inc.
TriTech Technologies Inc.
Vulcanium Plating Systems, Div. of Industrial Titanium Corp.
Walgren Co.

Infrared

Ciscan Industries Ltd.
Cleveland Process Corp.
Eclipse Combustion Inc.
Heraeus Amersil Inc.
Indesco Products Inc.
Research Inc.
Solar Products Inc.
Watlow Electric Mfg. Co.

Steam Boilers

Chromalox
Malsbary Cleaning Systems
National Combustion Co. Inc.

HOIST CONTROLLERS

Absolute Finishing Technology Associates Co. Inc.
American Plating Systems, Div. of Stewart Technologies Inc.
AmeriChem Engineering Services
Atotech USA Inc.
Baker Co., M.E.
Baker Technology Associates Inc.
Brian Co. Ltd., M.A.
Coscina Associates Inc., Frank J.
Desco Inc.
Entone-OMI Inc.
FPI Systems Inc.
Finishing Equipment Inc.
Gretch Electronics Inc.
HBS Equipment Corp.
J. Brinkman Co. Ltd.
JPS Technologies Inc.
Jessup Engineering Inc.
Merion Software Associates Inc.
Mesa West Inc.
Mid-Western Processes Inc.
PMS Inc.
Plasfab Inc.
Plating Technology Equipment Div.
Spectra Precision
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
TriTech Technologies Inc.
Walgren Co.

HOISTS

Absolute Finishing Technology Associates Co. Inc.
Adroit Automation Inc.
American Plating Systems, Div. of Stewart Technologies Inc.
AmeriChem Engineering Services
Atotech USA Inc.
Automate Tech Inc.
Baker Co., M.E.
Belke Mfg. Co.
Brian Co. Ltd., M.A.
Camac Industries
Circuit Chemistry Equipment
Coscina Associates Inc., Frank J.
Desco Inc.
Eidschun Engineering Inc.
Entone-OMI Inc.
Excel Plating Technology Inc.
FPI Systems Inc.
Finishing Equipment Inc.
HBS Equipment Corp.
J. Brinkman Co. Ltd.
JPS Technologies Inc.
Jessup Engineering Inc.
KCH Services Inc., Engineered Services Div.
Leatherwood Plastics, Div. of Leatherwood Inc.
Mesa West Inc.
Mid-Western Processes Inc.
NCA Systems Inc.
PAL Sales Inc.
Plasfab Inc.
Price Industries Inc.
Rectifiers & Plating Equipment Ltd.
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
Therma-Tron-X Inc.
TriTech Technologies Inc.
U.C.R. Inc.
Upton Industries Inc.
Walgren Co.

HOODS—See Ventilation Equipment

HOT-DIP GALVANIZING EQUIPMENT

Barrett Centrifugals Inc.
CTI Ancor
Huber Construction Co. Inc.
Upton Industries Inc.
Zalcon Inc.

HULL CELLS—See Testing Equipment

IMMERSION HEATERS—See Heaters and Heat Transfer Equipment

IMPREGNATION EQUIPMENT AND PROCESSES

Hunter Products Inc.
Impco Inc.
Imprex Inc.
Ultraseal America Inc.

INDIUM PLATING—See Plating Processes

INSTALLATION CONTRACTORS

Plating and Anodizing Lines

A&T Engineering Associates
Chemical Equipment Fabricators Ltd.
ChromeTech Inc.
Corrotec Inc.
Excel Plating Technology Inc.
Fanta Equipment Co.
H&H Industrial Equipment
Industrial Plastics Fabricators Ltd.
J Mark Systems Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Lefort, L.W.
METFAB Technologies Inc.
NCA Systems Inc.
Nationwide Installation Corp.
Newcastle Industrial Contracting
PAL Sales Inc.
PKG Equipment Inc.
Plasfab Inc.
Remco Engineering
Sumrack Equipment and Supply Co. Inc. (SESCO)
Technic Inc., Equipment Div.
Tellkamp Systems Inc.
Therma-Tron-X Inc.
TriTech Technologies Inc.

Waste Treatment

A&T Engineering Associates
Advanced Chemical Systems Inc.
Beckhart Environmental Inc.
Capsule Environmental Engineering Inc.
Corrotec Inc.
DMP Corp.
Delta Pollution Control Inc.
Design Systems Inc.
Environmental Control Systems Inc.
H&H Industrial Equipment
Hawken Technologies
Herr Industrial Inc.
J Mark Systems Inc.

Jaca Corp.
Johnson Systems Inc.
Kontek Ecology Systems Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
MAB International Inc.
Manchester Corp.
Met-Chem Inc.
METFAB Technologies Inc.
Milbank Systems Inc.
Newcastle Industrial Contracting
North Coast Environmental Inc.
PKG Equipment Inc.
Prochemtech Intl. Inc.
Remco Engineering
Sumrack Equipment and Supply Co. Inc. (SESCO)
Technic Inc., Equipment Div.
TriTech Technologies Inc.
USFilter/Warrendale
Wastewater Treatment Systems
Water Technology

ION EXCHANGE EQUIPMENT—See Deionizers and Waste Recovery Processes and Equipment

ION EXCHANGE RESINS

Advanced Chemical Co.
Bayer Corp., Industrial Chemicals Div.
Bio-Recovery Systems Inc.
Dow Chemical Co.
Enviro-Pure Inc.
Graver Technologies Inc.
Kinetico Inc., Engineered Systems Div.
Purolite Co.
ResinTech Inc.
Rohm & Haas Co.
Sybron Chemical Inc.
USFilter/Permutit

IRON PLATING—See Plating Processes

LABORATORY SERVICES

ACT Laboratories Inc.
Accurate Engineering Labs, Div. of Rin Inc.
Anachem Laboratories
Applied Technical Services Inc.
Ashley Labs
Atomergic Chemetals Corp.
Lucent Technologies
National Exposure Testing
Platers Technical Service Inc.
Scientific Control Laboratories Inc.
Smith Precious Metals Co.
South Florida Test Service, Div. of Atlas Electric Devices Co.
Surface Science Western
White Laboratory & Co., J.

LATHES—See Polishing and Buffing Equipment

LEAD PLATING—See Plating Processes

LININGS—See Tank Liners, Drop-In and Tank Lining Services

LIQUID LEVEL CONTROLS

Braude (London) Ltd., E.
Cleveland Process Corp.
DMP Corp.
Flow Plus Inc.
Flowline
GLI International Inc.
HBS Equipment Corp.
Kontek Ecology Systems Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Lufran Inc.
Mesa West Inc.
Mid-Western Processes Inc.
PPG Pretreatment & Specialty Products
Process Technology Inc.
SERFILCO Ltd.
Sethco Div., Met-Pro Corp.
Southwest United Industries Inc.
Systematics Inc.
Technic Inc., Equipment Div.
TriTech Technologies Inc.
Yamada America Inc.

MAGNETS, PART RETRIEVAL

Belke Mfg. Co.
Shields Co.
TriTech Technologies Inc.

MASKING

Caps and Plugs

Duggan Masking Devices
Echo Supply
Harman Corp.
Jalco Associates
Mocap Inc.
Polaris Plastics Inc.
Protective Closures Co. Inc., Caplugs Div.
Sequoia Corp.
Shercon Inc.
Special Masking
StockCap, A Sinclair & Rush Co.

Liquid Compounds

Calgon Corp.
E/M Engineered Coating Solutions
Echo Supply
Entone-OMI Inc.
New England Rack Co. Inc.
Sanford Process Corp.
Technic Inc.
Thermo-Cote Inc.
Tolber Div., Pyramid Plastics Inc.

Tape

Acutape Corp.
Atotech USA Inc.
Echo Supply
Furon CHR
Harman Corp.
Jalco Associates
Mocap Inc.
Permacel
Preferred Tape Inc.
SMI Div., Sohn Mfg. Inc.
Sequel Corp.
Sequoia Corp.
Shercon Inc.
Special Masking
Specialty Tapes, Div. of RSW Inc.
StockCap, A Sinclair & Rush Co.
3M Co.
Tolber Div., Pyramid Plastics Inc.

Wax

Atotech USA Inc.
Zophar Mills Inc.

MASS FINISHING EQUIPMENT

Centrifugal Barrels

AAC Engineered Systems Inc.
Dreher Corp.
Finishing Associates Inc.
Grav-i-Flo Corp.
Harper Surface Finishing Systems Inc.
Mass Finishing Inc.
Otec Precision Finish Inc.
Richwood Industries
Technic Inc., Equipment Div.
Tipton US Corp.
TriTech Technologies Inc.
USFilter/VL Rampe

Centrifugal Disks

AAC Engineered Systems Inc.
Automated Finishing Inc.
Dreher Corp.
Finishing Associates Inc.
Grav-i-Flo Corp.
Greco Bros. Inc.
Harper Surface Finishing Systems Inc.
Hutson Inc., R.N.
Mikrofinish Inc.
Rosemont Industries Inc.
Roto-Finish Co. Inc.
Timesavers Inc.
Tipton US Corp.
USFilter/VL Rampe
Vibra Finish Co.
Vibra Finish Ltd.
Walther Corp.

Spindle Finishing
Almco Inc.
Iowa Engineered Processes Corp.
Turbo-Finish Process Laboratories

Tumbling Barrels
Almco Inc.
Aubin Co., A.E.
Automated Finishing Inc.
C&S Engineering Corp.
Deburring Laboratories
Dreher Corp.
Du-Lite Corp.
Finishing Systems Inc.
Gesswein & Co., Paul H.
Grav-i-Flo Corp.
Greco Bros. Inc.
Guyson Corp. of U.S.A.
Harper Surface Finishing Systems Inc.
Hunter Products Inc.
Kramer Industries Inc.
Nielsen & Sons Inc., John R.
Prosys Corp.
Roto-Finish Co. Inc.
Sweco Inc.
Technic Inc., Equipment Div.
Topline Mfg. Co.
Tru-Square Metal Products
Ultramatic Equipment Co.
U.S. Baird Corp.
USFilter/VL Rampe
Vibra Finish Co.
Vibra Finish Ltd.

Vibratory
Abrasive Finishing Inc.
Almco Inc.
Aubin Co., A.E.
Automated Finishing Inc.
Bel Air Finishing Supply Inc.
C&S Engineering Corp.
Chemtech Finishing Systems Inc.
Deburring Laboratories
Delrod Sales Corp.
Finishing Associates Inc.
Gesswein & Co., Paul H.
Grav-i-Flo Corp.
Harper Surface Finishing Systems Inc.
Kramer Industries Inc.
LS Industries
Matarese Finishing Services Inc.
Nova Finishing Systems Inc.
Raytech Industries, A Div. of Lyman Products Corp.
Roesler Metal Finishing USA LLC
Rosemont Industries Inc.
Roto-Finish Co. Inc.
Sweco Inc.
Technic Inc., Equipment Div.
Tipton US Corp.
Ultramatic Equipment Co.
USFilter/VL Rampe
Vibra Chem Co. Inc.
Vibra Finish Co.
Vibra Finish Ltd.

MASS FINISHING SUPPLIES

Agricultural Media
Green Products Co.
Vibra Finish Ltd.

Ceramic Media
Abrasive Finishing Inc.
Almco Inc.
C&S Engineering Corp.
Dreher Corp.
Electro Abrasives Corp.
Hoover Precision Products
K.C. Abrasive Co. Inc.
MacDermid Inc.
Polyflow Inc.
Richwood Industries
Roto-Finish Co. Inc.
Sil-trade USA Inc.
Technic Inc., Equipment Div.
3R Mineral & Mfg. Co.
Ultramatic Equipment Co.
United Abrasive Inc.
USFilter/VL Rampe
Vibra Finish Co.
Vibra Finish Ltd.
Washington Mills Ceramics Corp.
Wisconsin Porcelain Co.

Compounds
Abrasive Finishing Inc.
Almco Inc.
Automated Finishing Inc.
C&S Engineering Corp.
Calgon Corp.
Chemtech Finishing Systems Inc.
Deburring Laboratories
DeLong Equipment Co.
Delrod Sales Corp.
Dreher Corp.
EZE Products Inc.
Enequist Chemical Co. Inc.
Finishing Systems Inc.
Grav-i-Flo Corp.
Harper Surface Finishing Systems Inc.
Heatbath Corp.
Henkel Surface Technologies
Hubard-Hall Inc.
International Chemical Co.
JacksonLea, A Unit of Jason Inc.
Kramer Industries Inc.
Luster-On Products Inc.
MacDermid Inc.
Markee Corp.
McGean-Rohco Inc.
Meraco Inc.
Metal Chem Inc.
Mikro Industrial Finishing
Mosher Co. Inc.
New Age Chemical Inc.
Okuno Chemical Industries Co. Ltd.
Patclin Chemical Co. Inc.
Pax Surface Chemicals Inc.
Precision Finishing Inc.
REM Chemicals Inc.
Rosemont Industries Inc.
Roto-Finish Co. Inc.
Todco Industries Inc.
Tronex Chemical Corp.
Tru-Chem Co. Inc.
Ultramatic Equipment Co.
USFilter/VL Rampe
Vibra Finish Co.
Vibra Finish Ltd.
Walther Corp.
Working Solutions Inc.

Plastic Media
Almco Inc.
Automated Finishing Inc.
Composition Materials Co. Inc.
Polyflow Inc.
Richwood Industries
Roto-Finish Co. Inc.
Technic Inc., Equipment Div.
Ultramatic Equipment Co.
United Abrasive Inc.
USFilter/VL Rampe
Vibra Finish Co.
Vibra Finish Ltd.

Steel Media
Abbott Ball Co.
C&S Engineering Corp.
Composition Materials Co. Inc.
Hoover Precision Products
Richwood Industries
Technic Inc., Equipment Div.
Vibra Finish Co.
Vibra Finish Ltd.

Wood Pegs
Cleveland Black Oxide
Composition Materials Co. Inc.
Dreher Corp.
Kramer Industries Inc.
Pegco Process Laboratories Inc.
Richwood Industries
Ultramatic Equipment Co.
Vibra Finish Co.

MECHANICAL PLATING EQUIPMENT AND SUPPLIES
Acme Metal Finishing Co. Inc.
International Metals and Chemicals Group
MacDermid Inc.
McGean-Rohco Inc.
Metal Coatings International Inc.
New York Plating Technologies Inc.
Plating Systems & Technologies Inc.
Potters Industries Inc., An Affiliate of the PQ Corp.
Sil-trade USA Inc.
Technic Inc., Equipment Div.
3R Mineral & Mfg. Co.
Tru-Plate Process Inc.

METAL COLORING—See

Blackening and Antiquing Processes

MICROSCOPES—See Testing Equipment

MIXING AND AGITATING EQUIPMENT

Ametek Rotron
Bex Inc.
Brawn Mixer Inc.
Chemineer Inc., A Unit of Robbins & Myers Inc.
Dedoes Industries Inc.
EMI Inc.
Entone-OMI Inc.
Filter Pump Industries, Div. of Penguin Pumps Inc.
Indco Inc.
Jiffy Mixer Co. Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Morse Mfg. Co. Inc.
Nalge Co.
Plating Products Co. Inc.
SERFILCO Ltd.
Technic Inc., Equipment Div.
TriTech Technologies Inc.

NICKEL PLATING—See Plating Processes and Electroless Plating Processes

NITRIDE COATING PROCESSES

Balzers Materials
Houghton International Inc.
Houston Unlimited Inc.
Ipsen International Inc.
Kolene Corp.
Leybold Systems Inc.
Ulvac, North American Corp.

NOZZLES

Abrasive Blasting

Boride Products Inc.
Delavan Mfg. Co.
Norton Co.
Pangborn Corp.
Pauli Systems
Pressure Blast Mfg. Co. Inc.
Surface Automation Systems LLC
Uni-Spray Nozzles Inc.
USFilter/Wheelabrator
White Technologies Inc., S.S.

Air Blow-off

ITW Vortec
Spraying Systems Co.

Spray Washing and Rinsing

Bex Inc.
Heat Systems-Ultrasonics Inc.
Lechler Inc.
Spraying Systems Co.
Steinen Mfg. Co., Wm.
Technic Inc., Equipment Div.
Uni-Spray Nozzles Inc.

OIL SKIMMERS—See Water Pollution Control Processes and Equipment

ORP CONTROLS—See Water Pollution Control Processes and Equipment

OVENS

Drying

Acme-Fab, Div. AF Industries
Aichelin-Stahl Inc.
Cincinnati Industrial Machinery, Div. of Eagle Picher Industries Inc.
Cleveland Process Corp.
Eisenmann Corp., Finishing Systems Div.
LTG Technologies Inc.
New England Oven and Furnace Co.
Technic Inc., Equipment Div.
TriTech Technologies Inc.

Infrared

Solar Products Inc.

Other

Aichelin-Stahl Inc.
Cincinnati Industrial Machinery, Div. of Eagle Picher Industries Inc.
Consolidated Engineering Co.
Despatch Industries Inc.
Gehnrich Oven Sales Co.
Grieve Corp.
Ipsen International Inc.
Koch Sons LLC, George
LTG Technologies Inc.
Lucifer Furnaces Inc.
New England Oven and Furnace Co.
Oven Systems Inc.
Ronalco Inc.
Steelman Industries Inc.
Tech Systems Inc.
Technic Inc., Equipment Div.

PALLADIUM PLATING—See Plating Processes and Electroless Plating Processes

PARTS WASHERS

AAC Engineered Systems Inc.
ADF Systems Ltd.
Accel Corp.
Acme-Fab, Div. AF Industries
Aichelin-Stahl Inc.
Alexor Inc.
Alliance Mfg. Inc.
Almco Inc.
Atcor Corp.
Atotech USA Inc.
Automated Finishing Inc.
Baron Blakeslee Inc.
Barrett Centrifugals Inc.
Better Engineering Mfg. Inc.
Billco Mfg. Co.
Bowden Industries Inc.
Brookline Machinery Inc.
CAE Cleaning Technologies
CAE Ransohoff Inc.
CRC Industries Inc.
Chemcut Equipment Group, **Atotech USA Inc.**
Chiron America
Cincinnati Industrial Machinery, Div. of Eagle Picher Industries Inc.
Consolidated Engineering Co.
Coscina Associates Inc., Frank J.
Cuda Corp.
Detrex Corp., Equipment Div.
Durr Ecoclean
EZE Products Inc.
Electronic Controls Design Inc.
Environmental Services Group
FMT Inc.
FPI Systems Inc.
Final Phase Inc.
Finishing Equipment Inc.
Flo-Matic Corp.
Forward Technology Industries Inc.
General Production Devices, A Div. of Lift Industries Inc.
Goff Corp., Div. George Fischer Foundry Systems Inc.
Graymills Corp.
Greco Bros. Inc.
Guyson Corp. of U.S.A.
Hurri-Kleen Corp.
Hydro-Blast Inc.
Industrial Washing Machine Corp.
Ipsen International Inc.
Jensen Fabricating Engineers Inc.
Kemac Inc.
Kim Mfg. Inc.
Kleer-Flo Co.
Klever Kleen Corp.
Koch Sons LLC, George
LS Industries
LTG Technologies Inc.
Landa Inc.
Lewis Cleaning Systems LLC
Mart Corp.
METFAB Technologies Inc.
Metric Systems Corp.
Midbrook Inc.
Miraclean Cleaning Systems, Div. of Chautauqua Chemicals Co. Inc.
Nano-Master Inc.

PPG Pretreatment & Specialty Products
Polyfab Plastics & Supply
Precision Quincy Corp.
Pressure Island
Proceco Inc.
Proceco Ltd.
Prosys Corp.
REM Sales Inc., Pero Parts Cleaning Systems
Ramco Equipment Corp.
Roilgard Inc.
Roto-Jet of America Co. Inc.
Safety-Kleen Corp.
Sonicor Instrument Corp.
SurfTran, Div. of Robert Bosch Corp.
SystemOne Technologies Inc.
Tally Cleaning Systems, METFAB Engineering
Taylex Group
TriTech Technologies Inc.
USFilter/VL Rampe
Vibra Finish Co.
Vibra Finish Ltd.
Western Sonics

pH and ORP CONTROLS—See Water Pollution Control Processes and Equipment

pH METERS AND ELECTRODES—See Testing Equipment

PHOSPHATE COATING PROCESSES

A Brite Co.
ACI Chemicals Inc.
Aerocote Corp.
Alchem Corp.
Aldoa Co.
American Chemical & Equipment
American Chemical Products Corp.
Arcal Chemicals Inc.
Arconium
Atotech USA Inc.
Benchmark Inc.
BetzDearborn, Div. of Hercules Inc.
Birchwood Laboratories Inc.
Broco Products Inc.
Calgon Corp.
Carpenter Chemicals LC
Chemtech Finishing Systems Inc.
Coral Chemical Co.
Deveco Corp.
DuBois, Div. of Diversey Lever
EZE Products Inc.
Electrochemical Products Inc. (EPI)
Elf Atochem North America Inc.
Fremont Industries Inc.
Haviland Products Co.
Heatbath Corp.
Henkel Surface Technologies
Houghton Metal Finishing Co.
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Metal Chem Inc.
Metal Coatings International Inc.
Mid-State Chemical & Supply Corp.
Missouri Electrochem Inc.
New Surface Technologies
Oakite Products Inc., A Member of The Chemetall Group
Oliver Sales Co.
PPG Pretreatment & Specialty Products
Patclin Chemical Co. Inc.
Pavco Inc.
Prosco Inc.
REM Chemicals Inc.
Rin Inc.
Southern Industrial Chemicals Inc.
Stan Sax Corp.
Sur-Fin Chemical Corp.
Texo Corp.
Todco Industries Inc.
Triple-S Chemical Products Inc.
Tronex Chemical Corp.
Tru-Chem Co. Inc.
U.C.R. Inc.
Working Solutions Inc.

PICKLING AND BRIGHT DIPPING PROCESSES

A Brite Co.
ACI Chemicals Inc.
Advanced Chemical Co.
Albright & Wilson Americas
Alchem Corp.
Aldoa Co.
Arcal Chemicals Inc.
Atotech USA Inc.
Benchmark Inc.
Bison Corp.
Brent America Inc.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemical Solvents Inc.
Chemtech Finishing Systems Inc.
Columbia Chemical Corp.
Coral Chemical Co.
Deveco Corp.
DuBois, Div. of Diversey Lever
Electrochemical Products Inc. (EPI)
Electrochemicals
Enequist Chemical Co. Inc.
Engelhard Electro Metallics Div.
Entone-OMI Inc.
Freiborne Industries
Fremont Industries Inc.
Haviland Products Co.
Heatbath Corp.
Henkel Surface Technologies
Hesse & Cie., Dr.
Houghton International Inc.
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Kemkel Corp.
Kolene Corp.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Metal Chem Inc.
Metalline Corp.
Mid-State Chemical & Supply Corp.
Missouri Electrochem Inc.
Niacet Corp.
OMG Fidelity
Oakite Products Inc., A Member of The Chemetall Group
Occidental Chemical Corp.
Okuno Chemical Industries Co. Ltd.
PCT Technology Inc.
PPG Pretreatment & Specialty Products
Patclin Chemical Co. Inc.
Pavco Inc.
Pax Surface Chemicals Inc.
Plating Process Systems Inc.
Plating Resources Inc.
Puma Chemical
REM Chemicals Inc.
Rhone-Poulenc Basic Chemicals Co.
Rin Inc.
Rit-Chem Co. Inc.
Shipley Ronal
Solvay Interox Inc.
Stapleton Technologies
Starlite Technical Service Inc.
Stellar Solutions Inc.
Sur-Fin Chemical Corp.
Taskem Inc.
Technic Inc.
Texo Corp.
Todco Industries Inc.
Transene Co. Inc.
Triple-S Chemical Products Inc.
Tronex Chemical Corp.
Working Solutions Inc.

PIPE FITTINGS AND VALVES, ACIDPROOF

Asahi/America Inc.
BFGoodrich Co., Corzan Industrial Systems Div.
Camac Industries
Corning Inc.
Dow Chemical Co.
Duriron Co. Inc., Valve Div.
Eslon Thermoplastics, Div. of Sekisui America Corp.
Fluidix Inc.
George Fischer Inc.
Goad Co.
Harrington Industrial Plastics Inc.
Harvel Plastics Inc.
Hayward Industrial Products Inc.
Industrial Plastics Fabricators Ltd.
Nibco Inc.
Norton Performance Plastics Corp.
Plast-O-Matic Valves Inc.
Prolite Plastics Ltd.
Southwest United Industries Inc.
Spears Mfg. Co.
Special Plastic Systems Inc.

Thermoplastic Valves Inc.
Vanton Pump & Equipment Corp.

PLASTIC BLASTING MEDIA—See Blasting Media

PLASTIC TANKS—See Tanks

PLATING AND ANODIZING EQUIPMENT

(See also Brush Plating, Strip and Spot Plating, and Wire Plating Machines)

American Plating Systems, Div. of Stewart Technologies Inc.
AmeriChem Engineering Services
Apple Fabrication Co.
Atotech USA Inc.
Automate Tech Inc.
B&M Plastics Inc.
B&P Plating Supply, Div. of Behrens & Peatman LLC
Baker Co., M.E.
Belke Mfg. Co.
Brian Co. Ltd., M.A.
Burt Process Equipment
Camac Industries
Carolinch Co.
Chemtech Finishing Systems Inc.
ChromeTech Inc.
Circuit Chemistry Equipment
Coscina Associates Inc., Frank J.
Covofinish Co. Inc.
Desco Inc.
ECI Technology Inc.
Eidschun Engineering Inc.
Entone-OMI Inc.
Excel Plating Technology Inc.
FPI Systems Inc.
Fanta Equipment Co.
Finishing Equipment Inc.
Flo King Filter Systems, Custom Masters Inc.
Foresight Technologies
GET Systems Inc.
Galvanotech
Greco Bros. Inc.
HBS Equipment Corp.
Hardwood Line Mfg. Co.
Haviland Products Co.
Hesse & Cie., Dr.
IPEC
Imperial Industries Inc.
International Surface Technology Ltd.
J. Brinkman Co. Ltd.
Jessup Engineering Inc.
KCH Services Inc., Engineered Services Div.
KiwiTech International. Pty. Ltd.
L.C. Fabricators Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Luster-On Products Inc.
Manz Galvano-Technik GmbH
Meco Equipment U.S.A. Inc.
Mesa West Inc.
METFAB Technologies Inc.
Mid-Western Processes Inc.
Napco Inc.
New England Plastic Coated Products Inc.
OMG Fidelity
P.G. Industries Inc.
PAL Sales Inc.
PDI Inc.
PKG Equipment Inc.
PMS Inc.
Palm Commodities International Inc.
Plasfab Inc.
Plastinetics Inc.
Plating Engineering and Chemicals Co. Ltd.
Polyfab Plastics & Supply
Reliable Equipment Corp.
Sanford Process Corp.
Singleton Corp.
Stapleton Technologies
Stewart Technologies Inc.
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
Tellkamp Systems Inc.
Ultimate Systems Inc.
Unified Equipment Systems Inc.
Upton Industries Inc.
Vincent Metals Corp.
Walgren Co.
Wear-Cote International Inc.

PLATING PROCESSES

(See also Brush Plating Processes and Equipment)

Aluminum

New Materials Corp.

Brass

Accurate Engineering Labs, Div. of Rin Inc.
Acme Metal Finishing Co. Inc.
Benchmark Products Inc.
Chemtech Finishing Systems Inc.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Enequist Chemical Co. Inc.
Hesse & Cie., Dr.
JacksonLea, A Unit of Jason Inc.
Kurts & Wolfe Chemical Co. Inc.
MacDermid Inc.
McGean-Rohco Inc.
Mibus Inc.
Pax Surface Chemicals Inc.
Plating Products Co. Inc.
Puma Chemical
Rin Inc.
Shipley Ronal
Starlite Technical Service Inc.
Technic Inc.
Triple-S Chemical Products Inc.
U.C.R. Inc.
Zinex Corp.

Bronze

Acme Metal Finishing Co. Inc.
Advanced Chemical Co.
Atotech USA Inc.
Chemtech Finishing Systems Inc.
Covofinish Co. Inc.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Enequist Chemical Co. Inc.
Pax Surface Chemicals Inc.
Plating Products Co. Inc.
Puma Chemical
Rin Inc.
Shipley Ronal
Starlite Technical Service Inc.
Technic Inc.
Triple-S Chemical Products Inc.
Zinex Corp.

Cadmium

Alchem Corp.
Aldoa Co.
Atotech USA Inc.
Benchmark Products Inc.
Bison Corp.
Chemtech Finishing Systems Inc.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Entone-OMI Inc.
Heatbath Corp.
Henkel Surface Technologies
Hesse & Cie., Dr.
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Pavco Inc.
Pax Surface Chemicals Inc.
Plating Products Co. Inc.
Plating Resources Inc.
Puma Chemical
Rin Inc.
Schlotter, Dr. Ing. Max
Shipley Ronal
Starlite Technical Service Inc.
Taskem Inc.
Technic Inc.
Triple-S Chemical Products Inc.
TriTech Technologies Inc.
U.C.R. Inc.

Chromium

Albright & Wilson Americas
Aldoa Co.
Allied-Hunter Corp.
Atotech USA Inc.

Benchmark Products Inc.
Bison Corp.
Chemtech Finishing Systems Inc.
ChromeTech Inc.
Deveco Corp.
Entone-OMI Inc.
Hard Chrome Plating Consultants Ltd.
JacksonLea, A Unit of Jason Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
New Surface Technologies
Oliver Sales Co.
Pax Surface Chemicals Inc.
Puma Chemical
Rin Inc.
Starlite Technical Service Inc.
Taskem Inc.
Technic Inc.
Transene Co. Inc.
Triple-S Chemical Products Inc.

Cobalt
Chemtech Finishing Systems Inc.
Entone-OMI Inc.
MacDermid Inc.
Mibus Inc.

Copper
A Brite Co.
Accurate Engineering Labs, Div. of Rin Inc.
Acme Metal Finishing Co. Inc.
Albright & Wilson Americas
Alchem Corp.
Aldoa Co.
Atotech USA Inc.
Benchmark Products Inc.
Bison Corp.
Chemtech Finishing Systems Inc.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Entone-OMI Inc.
Henkel Surface Technologies
Hesse & Cie., Dr.
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Kai Science and Technology Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Mibus Inc.
New Surface Technologies
OMG *Fidelity*
Okuno Chemical Industries Co. Ltd.
Pax Surface Chemicals Inc.
Plating Process Systems Inc.
Plating Products Co. Inc.
Plating Resources Inc.
Puma Chemical
REM Chemicals Inc.
Rin Inc.
Schlotter, Dr. Ing. Max
Shipley Ronal
Starlite Technical Service Inc.
Stutz Co.
Swest Inc.
Taskem Inc.
Technic Inc.
Triple-S Chemical Products Inc.
TriTech Technologies Inc.
U.C.R. Inc.
Uyemura Corp.
Zinex Corp.

Gold
Advanced Chemical Co.
Auromet Corp.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Covofinish Co. Inc.
Degussa Hüls Corp.
Engelhard Electro Metallics Div.
Entone-OMI Inc.
Hesse & Cie., Dr.
JacksonLea, A Unit of Jason Inc.
Johnson Matthey Inc., Materials Technology Div.
Lucent Technologies
MacDermid Inc.
OMG Fidelity
Puma Chemical
Shipley Ronal
Smith Precious Metals Co.
Southern Industrial Chemicals Inc.
Swest Inc.
Technic Inc.
Tivian Industries Ltd.
Transene Co. Inc.
Uyemura Corp.
Zinex Corp.

Indium
Alpha Metals Inc.
Indium Corp. of America
Technic Inc.
Transene Co. Inc.

Iron
Chemtech Finishing Systems Inc.
Transene Co. Inc.

Lead and Lead Alloys
Chemtech Finishing Systems Inc.
Entone-OMI Inc.
General Chemical Corp.
Goldschmidt Industrial Chemical Corp.
JacksonLea, A Unit of Jason Inc.
MacDermid Inc.
Maclee Chemical Co. Inc.
McGean-Rohco Inc.
Shipley Ronal
Taskem Inc.
Technic Inc.
Transene Co. Inc.

Nickel and Nickel Alloys
A Brite Co.
Accurate Engineering Labs, Div. of Rin Inc.
Acme Metal Finishing Co. Inc.
Albright & Wilson Americas
Alchem Corp.
Aldoa Co.
Atotech USA Inc.
BASF Corp., Chemicals Div.
Benchmark Products Inc.
Bison Corp.
Chemtech Finishing Systems Inc.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Electrochemicals
Engelhard Electro Metallics Div.
Entone-OMI Inc.
Henkel Surface Technologies
Hesse & Cie., Dr.
Howard Hall International
IMC Americhem (International Metals & Chemicals)
International Metals and Chemicals Group
JacksonLea, A Unit of Jason Inc.
Lucent Technologies
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Metal Chem Inc.
Mibus Inc.
New Surface Technologies
OMG Fidelity
Okuno Chemical Industries Co. Ltd.
Oliver Sales Co.
Pavco Inc.
Pax Surface Chemicals Inc.
Plating Process Systems Inc.
Plating Products Co. Inc.
Plating Resources Inc.
Puma Chemical
Rin Inc.
Rit-Chem Co. Inc.
Shipley Ronal
Starlite Technical Service Inc.
Swest Inc.
Taskem Inc.
Technic Inc.
Transene Co. Inc.
Triple-S Chemical Products Inc.
U.C.R. Inc.
Uyemura Corp.
Zinex Corp.

Palladium and Palladium Alloys
Auromet Corp.
Engelhard Electro Metallics Div.
Entone-OMI Inc.
Johnson Matthey Inc., Materials Technology Div.
Lucent Technologies
Shipley Ronal
Southern Industrial Chemicals Inc.
Technic Inc.
Uyemura Corp.

Platinum
Auromet Corp.
Engelhard Electro Metallics Div.
Entone-OMI Inc.

Johnson Matthey Inc., Materials Technology Div.
Southern Industrial Chemicals Inc.
Technic Inc.

Rhodium

Acme Metal Finishing Co. Inc.
Auromet Corp.
Engelhard Electro Metallics Div.
Entone-OMI Inc.
Hoover & Strong Inc.
Johnson Matthey Inc., Materials Technology Div.
Lucent Technologies
Reliable-West Tech Inc.
Smith Precious Metals Co.
Southern Industrial Chemicals Inc.
Technic Inc.

Ruthenium

Engelhard Electro Metallics Div.
Entone-OMI Inc.
Lucent Technologies
Technic Inc.

Silver

Atotech USA Inc.
Auromet Corp.
Covofinish Co. Inc.
Electrochemical Products Inc. (EPI)
Engelhard Electro Metallics Div.
Hesse & Cie., Dr.
JacksonLea, A Unit of Jason Inc.
Johnson Matthey Inc., Materials Technology Div.
Lucent Technologies
Luster-On Products Inc.
MacDermid Inc.
Plating Products Co. Inc.
Puma Chemical
Reliable-West Tech Inc.
Schlotter, Dr. Ing. Max
Shipley Ronal
Smith Precious Metals Co.
Southern Industrial Chemicals Inc.
Technic Inc.
Transene Co. Inc.
Zinex Corp.

Tin and Tin Alloys

Acme Metal Finishing Co. Inc.
Alchem Corp.
Aldoa Co.
AmeriChem Engineering Services
Ames Metal Products Co.
Atotech USA Inc.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemtech Finishing Systems Inc.
Columbia Chemical Corp.
Deveco Corp.
Electrochemicals
Engelhard Electro Metallics Div.
Entone-OMI Inc.
General Chemical Corp.
Goldschmidt Industrial Chemical Corp.
Heatbath Corp.
Hectrio
Henkel Surface Technologies
Hesse & Cie., Dr.
Howard Hall International
JacksonLea, A Unit of Jason Inc.
Jaynor Inc.
Lucent Technologies
Luster-On Products Inc.
MacDermid Inc.
Maclee Chemical Co. Inc.
Mason Corp.
McGean-Rohco Inc.
Metal Chem Inc.
Mibus Inc.
OMG Fidelity
Pax Surface Chemicals Inc.
Plating Products Co. Inc.
Plating Resources Inc.
Schlotter, Dr. Ing. Max
Shipley Ronal
Starlite Technical Service Inc.
Stutz Co.
Taskem Inc.
Technic Inc.
Tivian Industries Ltd.
Triple-S Chemical Products Inc.
U.C.R. Inc.
Zinex Corp.

Zinc and Zinc Alloys

A Brite Co.
Accurate Engineering Labs, Div. of Rin Inc.
Acme Metal Finishing Co. Inc.
Alchem Corp.
Aldoa Co.
American Chemical & Equipment
Atotech USA Inc.
Benchmark Products Inc.
Bison Corp.
Canadian Finishing Systems Ltd.
Chemtech Finishing Systems Inc.
Columbia Chemical Corp.
Deveco Corp.
Electrochemical Products Inc. (EPI)
Electrochemicals
Entone-OMI Inc.
Heatbath Corp.
Henkel Surface Technologies
Hesse & Cie., Dr.
Howard Hall International
Hubard-Hall Inc.
JacksonLea, A Unit of Jason Inc.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Mibus Inc.
New Surface Technologies
Okuno Chemical Industries Co. Ltd.
Oliver Sales Co.
Pavco Inc.
Pax Surface Chemicals Inc.
Plating Products Co. Inc.
Plating Resources Inc.
Puma Chemical
Rin Inc.
Rit-Chem Co. Inc.
Schlotter, Dr. Ing. Max
Shipley Ronal
Starlite Technical Service Inc.
Taskem Inc.
Triple-S Chemical Products Inc.
Tronex Chemical Corp.
U.C.R. Inc.
Uyemura Corp.
Westbrook LLC
Zinex Corp.

PLUGS—See Masking, Caps and Plugs

POLISHING AND BUFFING EQUIPMENT

(See also Belt Polishing)

Acme Mfg. Co.
CIMID
CS Unitec
Contact Rubber Corp.
Curtin-Hebert Co. Inc.
Dan Technology
Finishing Associates Inc.
Gesswein & Co., Paul H.
Grinding & Polishing Machinery Corp.
Hammond Machinery Inc.
Harper Surface Finishing Systems Inc.
Hill Acme Co.
Iding Co. Inc., M.P.
JacksonLea, A Unit of Jason Inc.
Kramer Industries Inc.
McKean Machinery Sales Inc.
Metabo Corp.
Munson Machinery Co. Inc.
Olean Finishing Machine Co. Inc.
Reliable Equipment Corp.
Sawyer and Smith Corp.
Schaffner Mfg. Co. Inc.
Spartan Felt Co.
Timesavers Inc.
TriTech Technologies Inc.
Union Tool Corp.
Wheel Doctor

POLLUTION CONTROL—See Air Pollution Control and Water Pollution Control

PORCELAIN ENAMELING

Equipment

Can-Eng Mfg. Ltd.
Eisenmann Corp., Finishing Systems Div.
ITW Gema
ITW Ransburg Electrostatic Systems
Koch Sons LLC, George
Nordson Corp.
Nutro Machinery Corp.
Ronalco Inc.

Frits

Ferro Corp., Powder Coatings Div.
Hommel Co., O.
Miles Inc.

POWER SUPPLIES

Aldonex Inc.
American Plating Systems, Div. of Stewart Technologies Inc.
AmeriChem Engineering Services
Baker Technology Associates Inc.
Chemtech Finishing Systems Inc.
Clinton Power, Subsidiary of Benjamin Power Co.
Controlled Power Co.
Darrah Electric Co.
Delta D.C. Power Inc.
Dynapower Corp.
Dynatronix Inc.
Entone-OMI Inc.
Environmental Plating Technology Inc.
Excel Plating Technology Inc.
HBS Equipment Corp.
Hendor-PE Inc.
IPR Systems Inc.
J. Brinkman Co. Ltd.
Keystone Electric Co. Inc.
King Corp., Larry
Liquid Development Co.
Mesa West Inc.
Neeltran Inc.
North American Rectifier Ltd.
PDI Inc.
PWR Inc.
Power Conversion Corp.
Precision Process Equipment Inc.
Process Electronics Corp.
Rapid Power Technologies Inc.
Rectifiers & Plating Equipment Ltd.
Robicon, A Subsidiary of High Voltage Engineering Corp.
SanRex Corp.
Sifco Selective Plating, Div. of Sifco Industries Inc.
Spang Power Electronics
Sunbelt Systems
Technic Inc., Equipment Div.
TecNu
Trilectron Industries Inc.
Zinex Corp.

PUMPS

Corrosive Chemicals

ABS Pumps Inc.
Ansimag Inc.
BJM Corp.
Barnant Co.
Braude (London) Ltd., E.
Camac Industries
Carver Pump Co.
Chemtech Finishing Systems Inc.
Corode B.V.
Crane Co., Chempump Div.
Cyclone Pumps
DMP Corp.
Excel Plating Technology Inc.
Filter Pump Industries, Div. of Penguin Pumps Inc.
Finish Thompson Inc.
Flo King Filter Systems, Custom Masters Inc.
Flowserve Corp.
Fluidpak Inc.
Fybroc Div., Met-Pro Corp.
Gusher Pumps Inc.
Harrington Industrial Plastics Inc.
Hendor-PE Inc.
Hoover Container Sales & Service Inc., Subsidiary of Hoover Group Inc.
ITT Jabsco
Industrial Filter & Pump Mfg. Co.
Isco Inc., Environmental Div.
Iwaki Walchem Corp.
LMI, Div. of Milton Roy
Little Giant Pump Co.
Magnatex Pumps Inc.
March Mfg. Co. Inc.
Osmonics Inc.
Plasmag Pump Co., Div. of Murdock Co.
Plating Products Co. Inc.
Plating Supplies International Inc.
Poly Products Corp.
Pulsafeeder Inc., A Unit of Idex Corp.
Pulse Instruments
Ryan Herco Products Corp.
SERFILCO Ltd.
Sethco Div., Met-Pro Corp.
Siebec
Summit Scientific Corp.
Technic Inc., Equipment Div.
Treatment Products Corp.
TriTech Technologies Inc.
Vanton Pump & Equipment Corp.
Walrus Pump & Filtration LLC
Warrender Ltd.
Webster Pumps
Wilden Pump & Engineering Co.
Yamada America Inc.

Diaphragm

All-Flo Pump Co.
Bromley Inc., B.A.
Chemtech Finishing Systems Inc.
LMI, Div. of Milton Roy
ProMinent Fluid Controls Inc.
Pumper Parts LLC
Sperry & Co., D.R.
TriTech Technologies Inc.
Versa-Matic Pump Co.
Warren Rupp Inc., A Unit of Idex Corp.

Drum

Camac Industries
Chemtech Finishing Systems Inc.
Filter Pump Industries, Div. of Penguin Pumps Inc.
Filter Specialists Inc.
Finish Thompson Inc.
Galway Pumps
ITT Jabsco
Indco Inc.
Lutz Pumps Inc.
Plating Supplies International Inc.
SERFILCO Ltd.
Sethco Div., Met-Pro Corp.
Summit Scientific Corp.
Technic Inc., Equipment Div.
TriTech Technologies Inc.
Vanton Pump & Equipment Corp.
Wilden Pump & Engineering Co.

Magnetic Drive Centrifugal

Ansimag Inc.
Chemtech Finishing Systems Inc.
Filter Pump Industries, Div. of Penguin Pumps Inc.
Finish Thompson Inc.
Flowserve Corp.
Harrington Industrial Plastics Inc.
Hendor-PE Inc.
Iwaki Walchem Corp.
Magnatex Pumps Inc.
March Mfg. Co. Inc.
Mefiag Div., Met-Pro Corp.
SERFILCO Ltd.
Sethco Div., Met-Pro Corp.
Siebec
Warrender Ltd.

Metering

Aqua Care Systems Inc., Filtration Systems Div./Metering Pump Group
Barnant Co.
Bran + Luebbe
LMI, Div. of Milton Roy
Plast-O-Matic Valves Inc.
ProMinent Fluid Controls Inc.
Pulsafeeder Inc., A Unit of Idex Corp.
SERFILCO Ltd.
TriTech Technologies Inc.

RACKS FOR PLATING AND ANODIZING

(See also Anodizing, Titanium Racks)

Able Rack Co.
Accurate Rack Co.
Adjust-A-Rak Inc.
An-Kor Plating Rack Co. Inc.
Apex Rack and Coating Co.
Associated Rack Corp.
AstroCosmos Metallurgical Inc.
Belke Mfg. Co.
Burke Rack Inc.
Burlingham International
Carlson Erie Corp.
Chemtech Finishing Systems Inc.
Duggan Masking Devices
Electrolyte Devices Inc.
Entone-OMI Inc.
HBS Equipment Corp.
Hard Chrome Plating Consultants Ltd.
Heatbath Corp.

Ideal Rack Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
M+B Plating Racks Inc.
Mesa West Inc.
Mitchell-Bate Co.
National Rack Co.
New England Plastic Coated Products Inc.
New England Rack Co. Inc.
PKG Equipment Inc.
Patrick Co., P.N.
Philip Machine Co.
Plating Products Co. Inc.
Pro Rac Co. Inc.
Process Electronics Corp.
Rack Processing Co.
Roberts Chemicals Co. Inc.
Sequel Corp.
Servi-Sure Corp.
Shipley Ronal
Southeastern Rack Co.
Southwestern Rack Co.
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
Tilton Rack & Basket Corp.
TriTech Technologies Inc.
Universal Rack Co.
Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp.
West Coast Rack & Mfg. Inc.

RECTIFIER REPAIR SERVICES

Aldonex Inc.
Clinton Power, Subsidiary of Benjamin Power Co.
Darrah Electric Co.
Delta D.C. Power Inc.
Excel Plating Technology Inc.
IPR Systems Inc.
Rapid Power Technologies Inc.
Technic Inc., Equipment Div.

REFINERY SERVICES

Advanced Chemical Co.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Eastern Smelting & Refining Corp.
Engelhard Electro Metallics Div.
Garfield Refining Co.
Geib Refining Corp.
Handy & Harman, Precious Metals Refining Div.
Heraeus Precious Metals Management Inc.
Hoover & Strong Inc.
International Metals Reclamation Co.
Johnson Matthey Inc., Materials Technology Div.
Metalor USA Refining Corp.
Metz Metallurgical Corp.
Pease & Curren Inc.
Recontek Inc.
Reliable-West Tech Inc.
Sabin Metal Corp.
Shipley Ronal
Technic Inc.
United Refining and Smelting Co.
WIT Sales & Refining
Williams Advanced Materials

RESISTS

Atotech USA Inc.
Electrochemicals
Entone-OMI Inc.
MacDermid Inc.
Shipley Ronal
Thermo-Cote Inc.
Transene Co. Inc.

RESPIRATORS—See Safety Equipment

RHODIUM PLATING—See Plating Process

RINSE CONTROL SYSTEMS

Hardwood Line Mfg. Co.
Myron L Co.
PAL Sales Inc.
Pasco
Plating Resources Inc.
Poly Products Corp.

RUST REMOVERS

MacDermid Inc.
Pavco Inc.

RUTHENIUM PLATING—See Plating Processes

SAFETY EQUIPMENT

Absorbents for Spills and Leaks

ILC Dover Inc.
Jomac Inc.
Matarah Industries Inc.
New Pig Corp.
Sorbent Control Technologies Inc.

Containers and Storage Cabinets

Justrite Mfg. Co.
Protectoseal Co.

Face Shields and Goggles

Aden Safety
American Allsafe Co.
Direct Safety Co.
Lab Safety Supply Inc.
Mine Safety Appliances Co.
Willson Safety Products, Div. of WGM Safety Corp.

Fire Detection and Suppression Systems

Detector Electronics Corp.

Gas Detectors

MST Measurement Systems Inc.
Mine Safety Appliances Co.

Protective Clothing

Direct Safety Co.
ILC Dover Inc.
Jomac Inc.
Lab Safety Supply Inc.
Sara Glove Co. Inc.

Respirators

Bullard Co., E.D.
Direct Safety Co.
Mine Safety Appliances Co.
Racal Health & Safety Inc.

Signs

Americraft Co. Inc.
Direct Safety Co.
Justrite Mfg. Co.
Lab Safety Supply Inc.

SAMPLERS FOR WASTEWATER

American Sigma
BVS Inc.
Barnant Co.
Environmental Control Systems Inc.
Isco Inc., Environmental Div.
Ivek Corp.
Markland Specialty Engineering Ltd.
Plating Products Co. Inc.

SAND BLASTING—See Blasting Equipment

SCRATCH BRUSHES—See Brushes, Rotary

SCREEN PRINTING EQUIPMENT AND SUPPLIES

Chemcut Equipment Group, **Atotech USA Inc.**
Leatherwood Plastics, Div. of Leatherwood Inc.
Shipley Ronal

SELECTIVE PLATING—See Brush Plating and Strip and Spot Plating Equipment

SHOT—See Blasting Media, Metallic

SHOT PEENING—See Blasting Equipment and Blasting Media

SILVER METALLIZING SPRAYS

Jema-American Inc.
Technic Inc.

SILVER PLATING—See Plating Processes and Electroless Plating Processes

SISAL—See Buffs

SLUDGE HANDLING EQUIPMENT

Centrifuges

Alfa Laval Separation Inc.
Barrett Centrifugals Inc.
Hyde Products Inc.
Sanborn Technologies, A Waterlink Co.
TriTech Technologies Inc.
U.S. Centrifuge

Dryers

Alar Engineering Corp.
Beckhart Environmental Inc.
Consolidated Engineering Co.
Contaminant Recovery Systems Inc.
Delta Pollution Control Inc.
Diagenex Inc.
Duriron Co. Inc., Engineered Systems Group
Hones Inc., Charles A.
Industrial Filter & Pump Mfg. Co.
Leatherwood Plastics, Div. of Leatherwood Inc.
Met-Chem Inc.
Oven Systems Inc.
Palm Commodities International Inc.
Phibro-Tech Inc.
Salem Environmental
Sperry & Co., D.R.
TriTech Technologies Inc.
USFilter/JWI
Watropur Corp.

Filters

Alar Engineering Corp.
Beckhart Environmental Inc.
Burt Process Equipment
Contaminant Recovery Systems Inc.
Delta Pollution Control Inc.
Diagenex Inc.
Dry Vac Environmental
Duriron Co. Inc., Engineered Systems Group
Eimco Process Equipment Co.
Engineering Solutions, Div. of LST Industries LLC
Environmental Control Systems Inc.
EnviroSystems Inc.
Excel Plating Technology Inc.
Goodnature Products Inc.
Great Lakes Filter
Hoffland Environmental Inc.
IPEC
Industrial Filter & Pump Mfg. Co.
Komline-Sanderson Engineering Corp.
Kontek Ecology Systems Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Lenser Filtration Inc.
Met-Chem Inc.
Mid-Western Processes Inc.
Netzsch Inc.
Oberlin Filter Co.
Olds Filtration Engineering Inc.
Pacific Press
Parkson Corp.
Precise Filtration Products Inc.
SERFILCO Ltd.
Sperry & Co., D.R.
Star Systems Filtration Div., Hilliard of South Carolina Inc.
Summit Scientific Corp.
Sumrack Equipment and Supply Co. Inc. *(SESCO)*
Technic Inc., Equipment Div.
USFilter/JWI
Water and Wastewater Equipment Co., Div. of Phil-Mar Equipment Inc.
Waterlink/Lanco Environmental Products

SOLVENT RECOVERY EQUIPMENT

Baron Blakeslee Inc.
Branson Ultrasonics Corp.
CB Mills, Div. of Chicago Boiler Co.
Calfran International Inc.
Consolidated Mfg. of Pittsburgh (CMP)
Corning Inc.
Detrex Corp., Equipment Div.
Finish Thompson Inc.
Giant Distillation & Recovery Co.
Hoyt Corp.
Kleer-Flo Co.
Met-Pro Corp., Systems Div.
Procedyne Corp.
Solvent Kleene Inc.
United Air Specialists Inc.
Westport Environmental Systems

SOLVENTS

AIBP Inc.
AlliedSignal Inc., Fluorine Products
American Chemical Products Corp.
Arcal Chemicals Inc.
Ashland Chemical Co., Div. of Ashland Inc.
Brent America Inc.
Calgon Corp.
Delta Foremost Chemical Corp.
Dow Chemical Co.
DuBois, Div. of Diversey Lever
DuPont Co.
Dynaloy Inc.
EZE Products Inc.
Entone-OMI Inc.
Environmental Solvents Corp.
Exxon Chemical Co.
ICI Americas Inc., General Chemicals Dept.
International Specialty Products
JNJ Industries Inc.
Kleer-Flo Co.
Kraft Chemical Co.
LPS Laboratories Inc.
Metal Coatings International Inc.
Mid-State Chemical & Supply Corp.
OMG Fidelity
Occidental Chemical Corp.
Patclin Chemical Co. Inc.
Rochester Midland Corp.
S&S Industrial Services
Solvent Kleene Inc.
Terpene Technologies Inc.
Texo Corp.
Thermo-Cote Inc.
Tower Chemical Corp.
Working Solutions Inc.
WSI Chemical Inc.

SPIN DRYERS—See Drying Equipment

SPRAY WANDS, PRETREATMENT

DuBois, Div. of Diversey Lever
Electro-Steam Generator Corp.
Fremont Industries Inc.

STOP-OFFS—See Masking and Resists

STRIP AND SPOT PLATING EQUIPMENT

Advanced Plating Technologies Inc.
AmeriChem Engineering Services
B&M Plastics Inc.
Carolinch Co.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Degussa Hüls Corp.
Eidschun Engineering Inc.
Engelhard Electro Metallics Div.
Entone-OMI Inc.
Fab-Tech
Galvanotech
International Surface Technology Ltd.
Meco Equipment U.S.A. Inc.
METFAB Technologies Inc.
Phoenix Process Technologies Inc.
Precision Process Equipment Inc.
Richcraft Designs Inc.
Shipley Ronal
Stewart Technologies Inc.

Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
Technic Inc., Surface Finishing Technologies
Vincent Metals Corp.

STRIPPERS, METAL

ACI Chemicals Inc.
Advanced Chemical Co.
Alchem Corp.
Aldoa Co.
American Chemical Products Corp.
Arcal Chemicals Inc.
Atotech USA Inc.
Benchmark Products Inc.
Bison Corp.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Chemtech Finishing Systems Inc.
Coral Chemical Co.
Covofinish Co. Inc.
Deveco Corp.
Electrochemicals
Enequist Chemical Co. Inc.
Engelhard Electro Metallics Div.
Entone-OMI Inc.
Haviland Products Co.
Heatbath Corp.
Hubard-Hall Inc.
King Corp., Larry
Kolene Corp.
Luster-On Products Inc.
MacDermid Inc.
McGean-Rohco Inc.
Metal Chem Inc.
Metal Coatings International Inc.
Metalx Inc.
Missouri Electrochem Inc.
OMG Fidelity
Okuno Chemical Industries Co. Ltd.
PPG Pretreatment & Specialty Products
Patclin Chemical Co. Inc.
Pax Surface Chemicals Inc.
Phibro-Tech Inc., Environmental Recovery Services Div.
Plating Resources Inc.
Rin Inc.
Savitt Industrial Products Inc.
Shipley Ronal
Starlite Technical Service Inc.
Sur-Fin Chemical Corp.
Surface Technology Inc.
Taskem Inc.
Technic Inc.
Thermo-Cote Inc.
Tivian Industries Ltd.
Todco Industries Inc.
Triple-S Chemical Products Inc.
Tronex Chemical Corp.
U.C.R. Inc.
Uyemura Corp.

SULFONATORS—See Water Pollution Control

Processes and Equipment

TANK LINERS, DROP-IN

Advanced Materials Inc.
American Lining Corp.
B&P Plating Supply, Div. of Behrens & Peatman LLC
Bulk Lift International Inc.
C&M Liner Co. Inc.
CDF Corp.
Carson Mfg. Co.
Chem-Tainer Industries
Chemtech Finishing Systems Inc.
Edlon-PSI, Unit of Robbins & Myers Inc.
Excel Plating Technology Inc.
Fab-Seal Industrial Liners Inc.
Fabrico Environmental Liners Inc.
Flexi-Liner Corp.
Foresight Technologies
Global Industrial Liner Inc.
Just Liners Inc.
Kentain Products Ltd.
Leatherwood Plastics, Div. of Leatherwood Inc.
Mid-America Industrial Liners Inc.
Mid-America Plastics
New England Plastic Coated Products Inc.
Plasfab Inc.
Protech Floorings & Linings Inc.
Rivas Co., Fred B.
Röchling Engineered Plastics
Specialty Plastic Fabricators Inc.
Stein & Associates Inc., Norman
Sumrack Equipment and Supply Co. Inc. (SESCO)
Technic Inc., Equipment Div.
TriTech Technologies Inc.
Unit Liner Co.
U.S. Liner Co.
U.S. Plastic Corp.
Witt Associates Ltd., F.C.

TANK LINING SERVICES

Arbonite, Div. of P&R Industries
Goad Co.
Leatherwood Plastics, Div. of Leatherwood Inc.
Moon Fabricating Corp.
New England Plastic Coated Products Inc.
P.G. Industries Inc.
Paterson Rubber Co.
Poly-Bond Mfg. Co.
Stein & Associates Inc., Norman
Tarus Equipment Co.
Viatec/Hastings Engineered Systems

TANKS, PLASTIC AND STEEL

AB Plastics Inc.
Advanced Materials Inc.
Air Chem Systems Inc.
AmeriChem Engineering Services
Apex Rack and Coating Co.
Apple Fabrication Co.
Atlantech **Process Technology Inc.**
Atlas Minerals & Chemicals Inc.
Automate Tech Inc.
B&M Plastics Inc.
B&P Plating Supply, Div. of Behrens & Peatman LLC
BFGoodrich Co., Corzan Industrial Systems Div.
Baker Co., M.E.
Belding Tank Technologies Inc.
Birchwood Laboratories Inc.
Braude (London) Ltd., E.
Burt Process Equipment
CDF Corp.
CTI Ancor
Carlson Erie Corp.
Carolinch Co.
Chem-Tainer Industries
Chemical Equipment Fabricators Ltd.
Chemtech Finishing Systems Inc.
Cincinnati Industrial Machinery, Div. of Eagle Picher Industries Inc.
Clawson Tank Co.
Coscina Associates Inc., Frank J.
Desco Inc.
Duall Div., Met-Pro Corp.
Entone-OMI Inc.
Excel Plating Technology Inc.
FPI Systems Inc.
Fab-Tech
Foresight Technologies
Goad Co.
Greco Bros. Inc.
Grewe Plastics
HBS Equipment Corp.
Hardwood Line Mfg. Co.
Harrington Industrial Plastics Inc.
Harrison Plastic Systems Inc.
Haviland Products Co.
Heil Process Equipment, Div. of Xerxes Corp.
Hoover Container Sales & Service Inc., Subsidiary of Hoover Group Inc.
ILC Dover Inc.
Imperial Industries Inc.
Industrial Plastics Fabricators Ltd.
Intellect Systems & Marketing Inc.
J. Brinkman Co. Ltd.
Jensen Fabricating Engineers Inc.
Justrite Mfg. Co.
KCH Services Inc., Engineered Services Div.
Kerrco Inc.
Koch Engineering Co. Inc.
Kontek Ecology Systems Inc.
L.C. Fabricators Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Mesa West Inc.
Met-Chem Inc.
METFAB Technologies Inc.
Moon Fabricating Corp.
NCA Systems Inc.
Nalge Co.
Napco Inc.

New England Plastic Coated Products Inc.
P.G. Industries Inc.
PKG Equipment Inc.
Pavco Inc.
Plasfab Inc.
Plastech Inc.
Plastinetics Inc.
Plating Products Co. Inc.
Poly Processing Co.
Poly-Bond Mfg. Co.
Polyfab Plastics & Supply
Pro-Fab Mfg. Inc.
Prolite Plastics Ltd.
R-V Industries Inc.
Rack Processing Co.
Saranac Tank Inc.
Savitt Industrial Products Inc.
Singleton Corp.
Stein & Associates Inc., Norman
Summit Scientific Corp.
Sumrack Equipment and Supply Co. Inc. (SESCO)
Sweet Chemical Services Co. Inc.
Tarus Equipment Co.
Technic Inc., Equipment Div.
Terracon
Tri-Mer Corp.
TriTech Technologies Inc.
Unique Industries Inc.
U.S. Plastic Corp.
Viatec/Hastings Engineered Systems
Walgren Co.

TAPE—See Masking

TEMPERATURE CONTROLS

Chromalox
Cleveland Process Corp.
Extech Instruments Corp.
Fenwal Temperature Control
National Combustion Co. Inc.
Oven Industries Inc.
Partlow Corp.
Process Technology Inc.
Technic Inc., Equipment Div.
TriTech Technologies Inc.
Vulcanium Plating Systems, Div. of Industrial Titanium Corp.

TESTING EQUIPMENT

Adhesion

Electromatic Equipment Co. Inc.
Technic Inc., Equipment Div.

Analytical Instruments

ATI Orion Research
Asoma Instruments Inc., Spectro Analytical Instruments Group
Automation Products Inc.
Brinkmann Instruments Inc.
Buck Scientific
Chem Lab Supplies
Chema Technology Inc.
Cianflone Scientific Instruments Corp.
Dionex Corp.
ECI Technology Inc.
EG&G Instruments Inc.
EM Science
Elchema
Fischer Technology Inc.
Foss NIRSystems
Hanna Instruments Inc.
Hawk Creek Laboratory Inc.
Instruments SA Group
Ionics Inc., Separations Technology Div.
Kocour Co. Inc.
Laabs Inc.
Lachat Instrument
LaMotte Co.
Lazar Research Laboratories Inc.
Leco Corp.
Leeman Labs Inc.
Metorex Inc.
O·I·Analytical
PPG Pretreatment & Specialty Products
Perkin-Elmer Corp.
Red Bird Service
Sanda Corp.
Technic Inc., Equipment Div.
Tytronics Inc.
UIC Inc.
Veeco Industrial Measurement
Walgren Co.
Yamamoto-Metkishikenki Co. Ltd.

Cleanliness Monitors

King Corp., Larry
Photo Emission Technology Inc.

Corrosion Resistance

Atlas Electric Devices Co.
Atotech USA Inc.
EG&G Instruments Inc.
Electromatic Equipment Co. Inc.
Gamry Instruments Inc.
Gardner Co. Inc., Paul N.
Industrial Filter & Pump Mfg. Co.
Koslow Scientific Co.
Lawrence Electronics Co.
Q-Panel Lab Products
Singleton Corp.
TriTech Technologies Inc.

Current Density

Dynapower Corp.
Industrial Instruments Inc.

Dye Tracers

Tracer Products, Div. of Spectronics

Environmental

Atlas Electric Devices Co.
Chem Lab Supplies
Erichsen Instruments Inc.
Hach Co.
Hotpack Corp.
Industrial Filter & Pump Mfg. Co.
Q-Panel Lab Products

Hydrogen Embrittlement

Lawrence Electronics Co.

Metal Identification Kits

Industrial Instruments Inc.
Koslow Scientific Co.
Metal Samples Co. Inc.
Technicorp

Microhardness

NewAge Industries Inc., Testing Instruments Group
Wilson Instruments Div., Instron Corp.

Microscopes

Chem Lab Supplies
GEI International Inc.
Leco Corp.
Nikon Inc.
Titan Tool Supply Co.
Unitron Inc.
Zeiss Inc., Carl

On-Line Chemical Analyzers

Asoma Instruments Inc., Spectro Analytical Instruments Group
Entone-OMI Inc.
HBS Equipment Corp.
Lachat Instrument
McGean-Rohco Inc.
Metorex Inc.
Parker Systems, Div. of D.J. Parker Co.
Stewart Technologies Inc.
Systematics Inc.
VerdEco Technologies Ltd.
Walchem Corp.
Walgren Co.

pH Meters and Electrodes

ABB Kent Taylor Inc.
ATI Orion Research
Analytical Measurements Inc.
Barnant Co.
Elcometer Inc.
Engineered Systems & Designs
Extech Instruments Corp.
Fil-Chem Inc., Paul Frank Div.
Fisher Scientific
Foss NIRSystems
GLI International Inc.
Gardner Co. Inc., Paul N.
George Fischer Inc.
Hach Co.
Hanna Instruments Inc.
Hawk Creek Laboratory Inc.
Kernco Instruments Co. Inc.
LMI, Div. of Milton Roy
LaMotte Co.
Lazar Research Laboratories Inc.
Leeds & Northrup, A Unit of General *Signal*

McNab Inc.
Myron L Co.
Oxyphen Products Co.
Phoenix Electrode Co.
Pulse Instruments
Sensorex Inc.
SERFILCO Ltd.
Systematics Inc.
Technic Inc., Equipment Div.
TriTech Technologies Inc.

Plating Cells

King Corp., Larry
Kocour Co. Inc.
Lucent Technologies
McGean-Rohco Inc.
Plating Test Cell Supply Co.
Technic Inc., Equipment Div.

Roughness Profilers

King Corp., Larry
Optical Dimensions
UBM Corp.
Wyko Corp.

Stress in Plated Deposits

Custom Scientific Instruments
Dawn Electrochemical Engineering
Industrial Instruments Inc.
Kameras Instruments
King Corp., Larry
Specialty Testing & Development Co.

Surface Tension

CSC Scientific Co. Inc.
KSV Instruments
King Corp., Larry
Kocour Co. Inc.

Test Panels

ACT Laboratories Inc.
AMZ Corp.
Gardner Co. Inc., Paul N.
King Corp., Larry
McGean-Rohco Inc.
Metal Samples Co. Inc.
Plating Test Cell Supply Co.
Q-Panel Lab Products
Technic Inc., Equipment Div.

Test Paper Strips/Kits

EM Science
Fil-Chem Inc., Paul Frank Div.
Hach Co.
Hawk Creek Laboratory Inc.
ICI Americas Inc., General Chemicals Dept.
Kocour Co. Inc.
Koslow Scientific Co.
LaMotte Co.
S&K Reagents Inc.

Thickness

Asoma Instruments Inc., Spectro Analytical Instruments Group
Automation U.S.A.
CMI International Corp.
Cianflone Scientific Instruments Corp.
DeFelsko Corp.
Elcometer Inc.
Electromatic Equipment Co. Inc.
ElektroPhysik U.S.A. Inc.
Fischer Technology Inc.
Foerster Instruments Inc.
Gardner Co. Inc., Paul N.
Justech Inc.
Kett
King Corp., Larry
Kocour Co. Inc.
Magne-Gage Sales & Service Co. Inc.
Maxtek Inc.
Metorex Inc.
Micro-Metrics Co.
Röntgenanalytik Messtechnik GmbH
Teknocom Inc.
TriTech Technologies Inc.
Uniwest
Veeco Industrial Measurement
Wilkens-Anderson Co.

Wear Resistance

Gardner Co. Inc., Paul N.
Kameras Instruments
King Corp., Larry
Taber Industries

THERMAL SPRAY EQUIPMENT AND MATERIALS

Hobart Tafa Technologies Inc.
Metco Div., Perkin-Elmer
Miller Thermal Inc.
Norton Co.
Platt Bros. & Co.
Praxair Surface Technologies Inc.
Sermatech International Inc.
Tafa Inc.

TIN PLATING—See Plating Processes and Electroless Plating Processes

TITANIUM RACKS—See Anodizing

ULTRAFILTRATION EQUIPMENT—See Waste Recovery Processes and Equipment

ULTRASONIC CLEANING EQUIPMENT

Almco Inc.
Baron Blakeslee Inc.
Blue Wave Ultrasonics
Branson Ultrasonics Corp.
CAE Ultrasonics
Corpane Industries Inc.
Crest Ultrasonics Corp.
Detrex Corp., Equipment Div.
Durr Ecoclean
EZE Products Inc.
Environmental Services Group
Esma Inc.
Finishing Equipment Inc.
Forward Technology Industries Inc.
Heat Systems-Ultrasonics Inc.
Jensen Fabricating Engineers Inc.
Kemac Inc.
Krautkramer Branson
L&R Mfg. Co.
Lewis Cleaning Systems LLC
Magnus Equipment Group
METFAB Technologies Inc.
Miraclean Cleaning Systems, Div. of Chautauqua Chemicals Co. Inc.
Misonix Inc.
Nano-Master Inc.
Northeastern Sonics
Power Sonics LLC
Ramco Equipment Corp.
Rosemont Analytical
S&K Products International
SanRex Corp.
Sonicor Instrument Corp.
SurfTran, Div. of Robert Bosch Corp.
Technic Inc., Equipment Div.
Telsonic Ultrasonics
Tiyoda Mfg. U.S.A. Inc.
Ultra-Kool Inc.
Ultrasonic Power Corp.
Vacuum Plating Technology Corp.
Vapor Engineering Inc.
Western Sonics
Zenith Ultrasonics Inc.

USED EQUIPMENT

Asset Exchange Ltd.
Emerald Sales and Consulting
Enterprise Equipment Co. Inc.
Excel Plating Technology Inc.
Fanta Equipment Co.
Fantaco Inc.
Filter Equipment Sales Co.
H&H Industrial Equipment
H.K. Equipment Inc.
JSA
Lanco Corp.
Leatherwood Plastics, Div. of Leatherwood Inc.
Met-Chem Inc.
Reliable Equipment Corp.
Schneider and Associates Inc., John
Sumrack Equipment and Supply Co. Inc. (SESCO)
TFS Technologies
Technic Inc., Equipment Div.
Waste Treatment Equipment Specialties Co
Water and Wastewater Equipment

Co., Div. of Phil-Mar Equipment Inc.
Water Works, A Div. of Polydisc Inc.
Williamsville Buff Co.

UV CURING EQUIPMENT

Dymax Corp.
Fusion Systems Corp.
Hanovia Inc.
UVIII Systems Inc.

VACUUM COATING

Equipment

ALTA Group, Div. of Johnson Matthey
Advanced Vacuum Co. Inc.
BOC Gases
Balzers Materials
CTI-Cryogenics Div., Helix Technology Corp.
CVC Products Inc.
Commonwealth Scientific Corp.
Darly Custom Technology Inc.
Denton Vacuum Inc.
Dynavac, A Tenney Co.
First Light Technology Inc.
Galileo Vacuum Systems Div.
General Vacuum
H.K. Equipment Inc.
Hauzer Techno Coating USA, c/o Bodycote IMT
IGC Polycold Systems Inc.
Innotec Group Inc.
Innovac Corp.
Ion Tech Inc.
Ipsen International Inc.
Isoflux Inc.
Lesker Co., Kurt J.
Leybold Systems Inc.
Manitou Systems Inc.
Materials Research Corp.
Materials Science Inc.
Mill Lane Engineering Co. Inc.
Multi-Arc Inc.
Nordiko U.S.A. Inc.
Research & PVD Materials Corp.
Soleras Ltd.
Stokes Vacuum Inc.
TFS Technologies
Teledyne Brown Engineering, Hastings Instruments
Ulvac, North American Corp.
Vacuum Inc.
Vacuum Plating Technology Corp.
Varian Associates Inc., Vacuum Products Div.
Veeco Industrial Measurement
Vergason Technology Inc.

Gauges

Balzers Materials
MKS Instruments Inc.
Vacuum Research Corp.

Leak Detectors

Balzers Materials

Paints

Newchem Co.
Schwartz Chemical Co. Inc.
Technical Coatings Co. Ltd.

Pumps

Advanced Vacuum Co. Inc.
Ametek Rotron
Balzers Materials
CTI-Cryogenics Div., Helix Technology Corp.
CVC Products Inc.
CVI, Div. of Process Systems International
Edwards High Vacuum International
Galileo Vacuum Systems Div.
General Vacuum
Hull Corp., Vacuum Components Div.
IGC Polycold Systems Inc.
Innovac Corp.
Ipsen International Inc.
Kinney Vacuum Co.
Lesker Co., Kurt J.
Leybold Vacuum Products Inc.
Motor Guard Corp.
Pfeiffer Vacuum Inc.
Precision Plus Vacuum Parts Inc.
Stokes Vacuum Inc.
Ulvac, North American Corp.
Varian Associates Inc., Vacuum Products Div.

Supplies (Evaporants)

Academy Precision Materials, Div. of Academy Corp.
Atomergic Chemetals Corp.
Balzers Materials
Dynavac, A Tenney Co.
EM Industries Inc.
ESK Engineered Ceramics, Wacker Chemicals U.S.A. Inc.
Fil-Tech Inc.
GTE Sylvania, Emissive Products Div.
General Electric Co.
Heraeus Materials Technology Div.
Lesker Co., Kurt J.
Materials Research Corp.
Midwest Tungsten Service Inc.
Phifer Wire Products Inc.
Pure Tech Inc.
Refining Systems Inc.
Research & PVD Materials Corp.
Thermionic Products Co.
Vacuum Engineering & Materials Co. Inc.
Williams Advanced Materials

Targets

Academy Precision Materials, Div. of Academy Corp.
Atomergic Chemetals Corp.
Atramet Inc.
Balzers Materials
Cerac Inc.
Dynavac, A Tenney Co.
Engelhard Corp.-CLAL LP
GTE Sylvania, Emissive Products Div.
Handy & Harman, Industrial Products Group
Heraeus Materials Technology Div.
Indium Corp. of America
Johnson Matthey Inc., Materials Technology Div.
Materials Research Corp.
Materials Science International Inc.
Pure Tech Inc.
Refining Systems Inc.
Research & PVD Materials Corp.
Sputtering Materials Inc.
Target Materials Inc.
Tosoh SMD Inc.
Vacuum Engineering & Materials Co. Inc.
Williams Advanced Materials

VACUUM DEOILING SYSTEMS

Ipsen International Inc.

VACUUM IMPREGNATION—See Impregnation Equipment and Processes

VALVES—See Pipe Fittings and Valves, Acid Proof

VAPOR DEGREASERS—See Degreasers, Solvent Vapor and Immersion

VENTILATION EQUIPMENT

Blowers and Fans

AB Plastics Inc.
Air Chem Systems Inc.
Ceilcote Air Pollution Control
Duall Div., Met-Pro Corp.
Harrington Industrial Plastics Inc.
Illinois Blower Inc.
Industrial Plastics Fabricators Ltd.
Intellect Systems & Marketing Inc.
KCH Services Inc.
Midwest Air Products Co. Inc.
NCA Systems Inc.
Nalge Co.
Plastech Inc.
R-V Industries Inc.
Sonic Air Systems Inc.
Technic Inc., Equipment Div.
Tri-Mer Corp.
Vanaire Ltd.

Ductwork and Hoods

AB Plastics Inc.

Air Chem Systems Inc.
Automate Tech Inc.
B&M Plastics Inc.
Braude (London) Ltd., E.
Burt Process Equipment
ChromeTech Inc.
Conserve Engineering Co. LLC
Duall Div., Met-Pro Corp.
Epcon Industrial Systems Inc.
Excel Plating Technology Inc.
Fab-Tech
Fabco Plastics Wholesale Ltd.
Harrington Industrial Plastics Inc.
Harrison Plastic Systems Inc.
Harvel Plastics Inc.
Industrial Plastics Fabricators Ltd.
Intellect Systems & Marketing Inc.
KCH Services Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Midwest Air Products Co. Inc.
Moon Fabricating Corp.
NCA Systems Inc.
Napco Inc.
PKG Equipment Inc.
Plastech Inc.
Plastinetics Inc.
Plating Products Co. Inc.
Poly Products Corp.
Polyfab Plastics & Supply
Pro-Fab Mfg. Inc.
R-V Industries Inc.
ScrubAir Vent Systems Inc.
Stein & Associates Inc., Norman
Sumrack Equipment and Supply Co. Inc. (SESCO)
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
Tri-Mer Corp.
Vanaire Ltd.
Viatec/Hastings Engineered Systems

VIBRATORY PLATING MACHINES

AmeriChem Engineering Services
Cemco International Inc., A Div. of Vanguard Holdings Inc.
ECI Technology Inc.
International Surface Technology Ltd.
Mesa West Inc.
Technic Inc., Equipment Div.

VOLTMETERS—See Electrical Metering Equipment

WASHERS—See Parts Washers

WASTE DISPOSAL AND RECYCLING SERVICES

ACM Services Co. Inc.
Amax Metals Recovery Inc., Subsidiary of Amax Metals Inc.
American Nukem Corp.
Ashland Chemical Co., Div. of Ashland Inc.
CDS Environmental Services
Concord Resources Group Inc.
DC Products
Dayton Water Systems
Encycle/Texas Inc.
Envirite Corp.
Environmental Purification Industries
Environmental Waste Technology Inc.
EnviroPure Solutions
Great Lakes Environmental
Heritage Environmental Services LLC
Horsehead Resource Development Inc.
Inmetco
Johnson Systems Inc.
Laidlaw Environmental Services Inc.
Met Wool Inc.
Mobile Process Technology
Norris Environmental Services
Phibro-Tech Inc., Environmental Recovery Services Div.
Recontek Inc.
Rhone-Poulenc Basic Chemicals Co.
Stablex Canada Inc.
Thermonic Inc.
21st Century Environmental Management
USFilter Recovery Services Inc.
WMX Technologies
World Resources Co.

WASTE RECOVERY PROCESSES AND EQUIPMENT

Diffusion Dialysis

Compliance Systems Inc.
Graver Water Systems Inc., Div. of Graver Co.
Green Technology Group
Pure Cycle Environmental Technologies, Inc.
Water Treatment Technologies Inc.
Zero Discharge Technologies Inc.

Electrodialysis

Aqualytics, Div. of Graver Co.
Asahi Glass America Inc.
i^3 Inc.
Ionics Inc., Separations Technology Div.
Ionsep Corp.
Membranes International Inc.
Technic Inc., Equipment Div.
Trionetics Inc.
Vincent Metals Corp.
Zero Discharge Technologies Inc.

Electrolytic

Advanced Chemical Co.
American Plating Systems, Div. of Stewart Technologies Inc.
AmeriChem Engineering Services
Automate Tech Inc.
BEWT Systems Inc.
Baker Co., M.E.
Bio-Recovery Systems Inc.
Cemco International Inc., A Div. of Vanguard Holdings Inc.
Cognis Inc.
Covofinish Co. Inc.
Eco-Tec Inc.
Ecowater Industrial Systems
Enviromet Corp.
Environmental Control Systems Inc.
IPEC
Ionics Inc., Separations Technology Div.
Jaynor Inc.
Johnson Systems Inc.
Kinetico Inc., Engineered Systems Div.
L&T Technologies Inc.
Met-Pro Corp., Systems Div.
NCA Systems Inc.
Napco Inc.
Niagara Environmental Associates
Pollution Application Systems Co. Inc.
Precious Metals Processing Consultants Inc.
RRC Agmet Inc.
Rapid Power Technologies Inc.
Recovery Engineering & Sales Co.
Reliable-West Tech Inc.
Remco Engineering
Renovare International Inc.
SERFILCO Ltd.
Shipley Ronal
Sweet Chemical Services Co. Inc.
Technic Inc., Equipment Div.
Trionetics Inc.
USFilter/Memtek
Vincent Metals Corp.
Water Treatment Technologies Inc.

Evaporators/Stills

Advanced Chemical Systems Inc.
Alter Mfg. & Consulting Associates
Aqua-Chem Inc., Water Technologies Div.
Aqualogic Inc.
Automate Tech Inc.
Beta Control Systems Inc.
Bio-Recovery Systems Inc.
Burt Process Equipment
Calfran International Inc.
Castion Corp.
Compliance Systems Inc.
Corning Inc.
Environmental Control Systems Inc.
EnviroSystems Inc.
Finish Thompson Inc.
George Scott International Inc.
Houston Fearless 76 Inc.
Industrial Filter & Pump Mfg. Co.
Intellect Systems & Marketing Inc.
Ionics Inc., Separations Technology Div.
JPS Technologies Inc.
Kontek Ecology Systems Inc.

Landa Inc.
Licon Inc.
MacDermid Inc.
Manchester Corp.
Midwest Air Products Co. Inc.
Monitrol Inc.
NCA Systems Inc.
Napco Inc.
New England Plastic Coated Products Inc.
Palm Commodities International Inc.
Plastinetics Inc.
Pollution Application Systems Co. Inc.
Poly Products Corp.
Power Plant Service Inc.
ProdEcon Inc.
Progressive Recovery Inc.
QVF Process Systems Inc.
Roilgard Inc.
SPF Corp. of America
Samsco Inc.
Separation Technologists Inc.
Technic Inc., Equipment Div.
Technotreat Corp.
Treatment Products Corp.
USFilter/Memtek
Wastesaver Technologies
Water Systems Inc.
Water Technology
Water Treatment Technologies Inc.

Ion Exchange

Advanced Chemical Systems Inc.
Aqualogic Inc.
Argon-Rhodium Inc.
Automate Tech Inc.
Baker Co., M.E.
Bio-Recovery Systems Inc.
Burt Process Equipment
Carolinch Co.
Cognis Inc.
Compliance Systems Inc.
DMP Corp.
Dayton Water Systems
EG&G Environmental
Eco-Tec Inc.
Ecowater Industrial Systems
Environmental Control Systems Inc.
EnviroPure Solutions
Enviroserve Inc.
Graver Water Systems Inc., Div. of Graver Co.
Hydromatix Inc.
Industrial Filter & Pump Mfg. Co.
Ionics Inc., Separations Technology Div.
Kinetico Inc., Engineered Systems Div.
King Corp., Larry
Kontek Ecology Systems Inc.
L&T Technologies Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Manchester Corp.
METFAB Technologies Inc.
Mobile Process Technology
NCA Systems Inc.
Napco Inc.
Penfield Liquid Treatment Systems
R-V Industries Inc.
Recovery Engineering & Sales Co.
Reliable-West Tech Inc.
Remco Engineering
Separation Technologists Inc.
SERFILCO Ltd.
Sethco Div., Met-Pro Corp.
Solmetex
Sybron Chemical Inc.
Technic Inc., Equipment Div.
Tetra Technologies Inc.
Treatment Products Corp.
Trionetics Inc.
USFilter/IWT
Water Treatment Technologies Inc.

Membrane Filtration

ACG Technology Ltd.
Advanced Chemical Systems Inc.
Argon-Rhodium Inc.
Beta Control Systems Inc.
Blue Spring Corp.
Commodore Separation Technologies Inc.
Compliance Systems Inc.
Cuno Separations, Systems Div.
Dayton Water Systems
Dynatec Systems Inc.
Ecowater Industrial Systems
Environmental Control Systems Inc.
EnviroPure Solutions
Foresight Technologies
Graver Technologies Inc.
Hyde Products Inc.
Infinitex
Ionics Inc., Separations Technology Div.
Kinetico Inc., Engineered Systems Div.
Koch Membrane Systems Inc.
L&T Technologies Inc.
LCI Corp., Process Div.
Manchester Corp.
Membranes International Inc.
METFAB Technologies Inc.
MichDan Environmental Technologies Inc.
Micro-Set
Midbrook Inc.
Osmonics Inc.
PPG Pretreatment & Specialty Products
Penfield Liquid Treatment Systems
Pollution Application Systems Co. Inc.
Polylonix Separation Technologies Inc.
ProdEcon Inc.
Prosys Corp.
R-V Industries Inc.
RGF Environmental Systems Inc.
Rasco Inc.
Remco Engineering
Sanborn Technologies, A Waterlink Co.
Separation Technologists Inc.
Seprotech Systems Inc.
Snyder Filtration
Treatment Products Corp.
UFS Corp.
U.S. Centrifuge
USFilter/Memtek
W.E.S. Inc.
Water Treatment Technologies Inc.

Solvent Extraction

Cognis Inc.

WATER POLLUTION CONTROL PROCESSES AND EQUIPMENT

(See also Installation Contractors)

Carbon Adsorbers

Calgon Carbon Corp.
Carbtrol Corp.
Lewis Environmental Services Inc.
Treatment Products Corp.
TriTech Technologies Inc.

Chlorinators and Sulfonators

Brinecell Inc.
Capital Controls Co. Inc.
Chlorinators Inc.
Fischer & Porter Co.
TriTech Technologies Inc.
Vincent Metals Corp.
Wallace & Tiernan

Clarifiers

ACG Technology Ltd.
Advanced Chemical Systems Inc.
Alar Engineering Corp.
Andco Environmental Processes Inc.
Aqualogic Inc.
Automate Tech Inc.
Beckhart Environmental Inc.
Burt Process Equipment
DMP Corp.
Dagex Inc.
Delta Pollution Control Inc.
Duriron Co. Inc., Engineered Systems Group
Eimco Process Equipment Co.
Engineering Solutions, Div. of LST Industries LLC
Enprotec
Environmental Control Systems Inc.
Etus Inc.
Graver Water Systems Inc., Div. of Graver Co.
Great Lakes Environmental
Hoffland Environmental Inc.
Hudson Industries Inc.
IPEC
Industrial Filter & Pump Mfg. Co.
Koch Sons LLC, George
Kontek Ecology Systems Inc.
Leatherwood Plastics, Div. of Leatherwood Inc.
Manchester Corp.
Met-Chem Inc.

Met-Pro Corp., Systems Div.
Mid-Western Processes Inc.
Midbrook Inc.
Monroe Environmental Corp.
NCA Systems Inc.
Napco Inc.
New England Plastic Coated Products Inc.
Parkson Corp.
Pollution Application Systems Co. Inc.
Precise Filtration Products Inc.
Purac Engineering Inc., Div. of Anglian Water
R-V Industries Inc.
Romar Technologies Inc.
SERFILCO Ltd.
Sumrack Equipment and Supply Co. Inc. (SESCO)
Treatment Products Corp.
TriTech Technologies Inc.
USFilter/Memtek
Wastewater Treatment Systems
Water and Wastewater Equipment Co., Div. of Phil-Mar Equipment Inc.
Waterlink/Lanco Environmental Products

Cyanide Hydrolysis
Cyanide Destruct Systems Inc.

Electrocoagulation
Cure International Inc.
Kaspar Electroplating Corp.
Pasco

Electrolytic
Andco Environmental Processes Inc.
Technic Inc., Equipment Div.

Flocculants and Precipitation Agents
A Brite Co.
ACI Chemicals Inc.
Advanced Chemical Systems Inc.
Alchem Corp.
Aldoa Co.
Beckhart Environmental Inc.
Benchmark Products Inc.
Calgon Corp.
Chemtech Finishing Systems Inc.
Colloid Environmental Technologies Co., Subsidiary of American Colloid
Coral Chemical Co.
Degussa Hüls Corp.
Dow Chemical Co.
Enviro-Pure Inc.
Epoc Water Inc.
Etus Inc.
Henkel Surface Technologies
Hill Bros. Chemical Co.
Horsehead Resource Development Inc.
Houghton Metal Finishing Co.
KBF Pollution Management Inc.
Martin Marietta Magnesia Specialties
McGean-Rohco Inc.
Metal Chem Inc.
Metre-General Inc.
Mibus Inc.
Mid-State Chemical & Supply Corp.
Missouri Electrochem Inc.
Morton International Inc., Ventron Div.
Nalco Chemical Co.
Okuno Chemical Industries Co. Ltd.
Pavco Inc.
Pellu Systems Inc.
Premier Services Corp.
Rin Inc.
Romar Technologies Inc.
Southern Industrial Chemicals Inc.
Specialty Chemical Industry Corp.
Taskem Inc.
Texo Corp.
Unipure Environmental

Oil Skimmers
ACG Technology Ltd.
Abanaki Corp., Oil Skimmer Div.
Advanced Chemical Systems Inc.
Ambar Environmental Products
Aqueous Recovery Resources Inc.
Dynatec Systems Inc.
Enprotec
Hudson Industries Inc.
Hyde Products Inc.
MSC Liquid Filtration Corp.
Manchester Corp.
Met-Pro Corp., Systems Div.
METFAB Technologies Inc.
MichDan Environmental Technologies Inc.
Midbrook Inc.
New England Plastic Coated Products Inc.
Oil Skimmers Inc.
PPG Pretreatment & Specialty Products
Plasfab Inc.
Pollution Application Systems Co. Inc.
Treatment Products Corp.
Wayne Products Inc.

pH and ORP Controls
Advanced Chemical Systems Inc.
Analytical Measurements Inc.
Aqualogic Inc.
Aquametrix Ltd.
Automate Tech Inc.
Barnant Co.
Burt Process Equipment
Digital Analysis Corp.
Duriron Co. Inc., Engineered Systems Group
Dynatec Systems Inc.
Enprotec
Etus Inc.
GLI International Inc.
KCH Services Inc.
Kontek Ecology Systems Inc.
LMI, Div. of Milton Roy
Lakewood Instruments Inc., Div. of Osmonics
Leeds & Northrup, A Unit of General Signal
Mardon Control Systems Inc.
METFAB Technologies Inc.
Mid-Western Processes Inc.
NCA Systems Inc.
Osmonics Inc.
Pollution Application Systems Co. Inc.
Pulse Instruments
Romar Technologies Inc.
Sensorex Inc.
SERFILCO Ltd.
Sumrack Equipment and Supply Co. Inc. (SESCO)
Systematics Inc.
TBI-Bailey Controls Co.
Technic Inc., Equipment Div.
USFilter/Warrendale
Walchem Corp.
Walgren Co.

Polishing Filters
Contaminant Recovery Systems Inc.
Enprotec
Graver Technologies Inc.
Industrial Filter & Pump Mfg. Co.
Jarvis Mfg.
Met-Chem Inc.
Palm Commodities International Inc.
Parkson Corp.
Recovery Engineering & Sales Co.
Treatment Products Corp.
Turnkey Solutions Inc.
USFilter/Memtek

WIRE BRUSHES—See Brushes, Rotary

WIRE PLATING MACHINES
Carolinch Co.
Eidschun Engineering Inc.
METFAB Technologies Inc.
Plasfab Inc.
Technic Inc., Equipment Div.
Vincent Metals Corp.

WOOD PEGS—See Mass Finishing Supplies

ZINC PLATING—See Plating Processes

ZINCATES—See Aluminum, Processes for Plating on

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Companies in bold face are display advertisers in this edition.

A

A Brite Co. 8005 Sovereign Row Dallas, TX 75247 214-638-0465 888-822-7483 fax, 214-630-4849
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A&T Engineering Associates 104 Middle Quarter, Rte. 6 Woodbury, CT 06798 203-263-0265 fax, 203-266-4026

AAC Engineered Systems Inc. 2702 Cindel Dr., Unit 3 Cinnaminson, NJ 08077-2019 609-829-4500 800-435-3643 fax, 609-829-9112

AB Plastics Inc. 1287 U.S. Rt. 50, Bldg. A Milford, OH 45150 513-576-6333 fax, 513-576-6399

ABB Air Preheater Inc., Ehrsam Blast Systems 2101 N. Buckeye, P.O. Box 339 Abilene, KS 67410 785-263-4300 800-255-7910 fax, 785-263-3932

ABB Kent Taylor Inc. 1175 John St., P.O. Box 20550 Rochester, NY 14602-0550 716-292-6050 fax, 716-273-6207

ABS Pumps Inc. 140 Pond View Dr. Meriden, CT 06450 203-238-2700 fax, 203-238-0738

AC Molding Compounds S. Cherry St., P.O. Box 425 Wallingford, CT 06492 203-284-4334 800-523-2262 fax, 203-284-4306

ACG Technology Ltd. 6635 Kitimat Rd., Unit 34 Mississauga, Ont. L5N 6J2, Canada 905-567-4441 fax, 905-567-6623

ACI Chemicals Inc. 140 Industrial St. Lancaster, TX 75134 972-227-2241 fax, 972-227-7943

ACM Services Co. Inc. 1603 Jessup St., Unit #9 Wilmington, DE 19802 302-655-1860 fax, 302-426-1650

ACO Polymer Products Inc. 12080 Ravenna Rd., P.O. Box 245 Chardon, OH 44024-0245 216-285-7000 fax, 216-285-7005

ACT Laboratories Inc. 273 Industrial Dr., P.O. Box 735 Hillsdale, MI 49242 517-439-1485 fax, 517-439-1652

ADF Systems Ltd. 1302 19th St., N., P.O. Box 278 Humboldt, IA 50548-9918 515-332-5400 800-959-1191 fax, 515-332-4475

AIBP Inc. 1911 Huguenot Rd., Ste. 201, P.O. Box 36001 Richmond, VA 23235 804-378-8224 800-323-2070 fax, 804-378-8226

AIM Products Inc. 9 Rocky Hill Rd. Smithfield, RI 02917 401-232-2772 fax, 401-232-2802

ALTA Group, Div. of Johnson Matthey 195 Hartzell School Rd. Fombell, PA 16123-9518 412-452-1300 fax, 412-452-7701

AM Machinery Sales Inc. 186 Twining Bridge Rd. Newtown, PA 18940 215-860-8186 fax, 215-860-9772

AMZ Corp. 1600 Pennsylvania Ave. York, PA 17404 717-848-2565 fax, 717-854-7743

API Heat Transfer Inc. 2777 Walden Ave. Buffalo, NY 14225 716-684-6700 877-274-4328 fax, 716-694-2129
(*See our ad on page 621.*)

API Ketema Inc. 2300 W. Marshall Dr. Grand Prairie, TX 75051 972-647-2626 800-483-2263 fax, 972-641-1518
(*See our ad on page 621.*)

ATI Orion Research 529 Main St. Boston, MA 02129 617-242-3900 800-225-1480 fax, 617-242-7885

Abanaki Corp., Oil Skimmer Div. 17387 Munn Rd. Chagrin Falls, OH 44023 440-543-7400 800-358-7546 fax, 440-543-7404

Abatement Technologies 1705 Belle Meade Ct., Ste. 160 Lawrenceville, GA 30243 770-339-2600 fax, 770-339-2601

Abbott Ball Co. Railroad Pl., P.O. Box 330100 W. Hartford, CT 06133-0100 860-236-5901 fax, 860-233-1069
(*See our ad on page 119.*)

Able Rack Co. 6800 N. Broadway St. Louis, MO 63147 314-383-5225 fax, 314-383-5445

Abrasive Engineering & Mfg. 540 E. Old Hwy. 56 Olathe, KS 66061 913-764-6040 800-875-6040 fax, 913-764-0429

Abrasive Finishing Inc. 11770 Dexter Rd. Chelsea, MI 48118 734-475-9111 fax, 734-475-3300

Abrasive Service Co. Inc. 398 Broad St. Forestville, CT 06010 203-584-2091 800-569-1274 fax, 203-584-2313

Absolute Finishing Technology Associates Co. Inc. P.O. Box 11188 Jackson, MS 39283-1188 601-992-8155 fax, 601-992-8153
(*See our ad on page 618.*)

Abtex Corp. 89 Main St. Dresden, NY 14441 315-536-7403 fax, 315-536-0280

Academy Precision Materials, Div. of Academy Corp. 5531 Midway Park Pl., N.E. Albuquerque, NM 87109 505-343-9440 800-854-8595 fax, 505-343-9441

Accel Corp. 1825 E. Plano Pkwy. Plano, TX 75074 214-424-3525 fax, 214-424-7526

Accurate Engineering Labs, Div. of Rin Inc. 2707 W. Chicago Ave. Chicago, IL 60622 773-384-4522 fax, 773-384-8681
(*See our ad on page 16.*)

Accurate Rack Co. 253 Edgewood Ave. Hamilton, OH 45013 513-895-9100 fax, 513-895-0196

Acme Belt Recoating Inc. Cole & Arnold Sts. Quincy, MI 49082 517-639-8711 fax, 517-639-3304

Acme Metal Finishing Co. Inc. 1250 San Fernando Rd. Los Angeles, CA 90065 818-887-6255 fax, 213-887-3430

Acme Mfg. Co. 650 W. 12 Mile Rd. Madison Heights, MI 48071-2498 248-547-6700 fax, 248-547-0707

Acme-Fab, Div. AF Industries 11337 Williamson Rd. Cincinnati, OH 45241 513-489-3060 fax, 513-489-6018

gbccompAcutape Corp. 10 Gold St. Norwalk, CT 06850 203-849-9875 800-722-0133 fax, 203-849-0765

Aden Safety 5801 Safety Dr., N.E. Belmont, MI 49306 616-784-6200 fax, 616-784-7870

Adjust-A-Rak Inc. 5 Stahuber Ave. Union, NJ 07083 908-688-0800 fax, 908-688-0718
(*See our ad on page 709.*)

Adroit Automation Inc. 480 E. 76th Ave., Bldg. 5 Denver, CO 80229 303-288-8868 800-288-8868 fax, 303-288-8887
(*See our ad on page 640.*)

Advanced Chemical Co. 105 Bellows St. Warwick, RI 02888 401-785-3434 800-553-3568 fax, 401-941-9210

Advanced Chemical Systems Inc. 2612 S. Greeley Milwaukee, WI 53207 414-486-0528 fax, 414-486-0529
(*See our ad on pae 811.*)

Advanced Materials Inc. 524 Golf Course Rd. Tallapoosa, GA 30176 770-574-8839 800-822-8881 fax, 770-574-8889

Advanced Plating Technologies Inc. 4 Harmar St. Warren, PA 16365 814-726-9400 fax, 814-726-9403

Advanced Vacuum Co. Inc. 1215 Business Pkwy., N. Westminster, MD 21157 410-876-8200 800-272-2525 fax, 410-876-5820

Aercology Inc. 8 Custom Park Dr. Old Saybrook, CT 06475 860-399-7941 800-826-6123 fax, 860-399-7049

Aero-Blast Products Inc. 630 E. Bronson St. South Bend, IN 46601 219-288-0461 fax, 219-234-0792

Aerocote Corp. 408 Jensen Dr., P.O. Box 15849 Houston, TX 77220 713-224-6185 800-883-5621 fax, 713-223-5229

Aget Mfg. Co. 1408 E. Church St., P.O. Box 248 Adrian, MI 49221 517-263-5781 fax, 517-263-7154

Agmet Metals Inc. 7800 Medusa St. Oakwood Village, OH 44146 216-439-7400 fax, 216-439-7446

Aichelin-Stahl Inc. 810-C N.W. Main St. Lee's Summit, MO 64086 816-525-8400 fax, 816-525-8488

Air Chem Systems Inc. 15222 Connector Ln. Huntington Beach, CA 92649 714-897-1017 fax, 714-897-0639
(*See our ad on page 787.*)

Air Quality Engineering Inc. 3340 Winpark Dr. Minneapolis, MN 55427-2083 612-544-4426 800-328-0787 fax, 612-544-4013

AirCel Corp. 3525 Castle Ln. Alcoa, TN 37701 423-681-7066 fax, 423-681-7069

Alar Engineering Corp. 9651 W. 196th St. Mokena, IL 60448 708-479-6100 fax, 708-479-9059

Albax Inc. 100 Aniline Ave. Holland, MI 49424 616-396-2411 800-535-2411 fax, 616-396-9426

Albemarle Corp. 451 Florida St. Baton Rouge, LA 70801 225-388-7402 800-535-3030 fax, 225-388-7848

Albright & Wilson Americas P.O. Box 4439 Glen Allen, VA 23058-4439 804-968-6300 fax, 804-968-6385

Alchem Corp. 525 W. Liberty St. Medina, OH 44256 330-725-2436 fax, 330-725-8354
(*See our ad on page 9.*)

Alconox Inc. 9 E. 40th St., #200 New York, NY 10016-0402 212-532-4040 fax, 212-532-4301

Aldoa Co. 12727 Westwood Ave. Detroit, MI 48223 313-273-5705 fax, 313-273-0310
(*See our ad on page 18.*)

Aldonex Inc. 2917 St. Charles Rd., P.O. Box 148 Bellwood, IL 60104 708-547-5663 fax, 708-547-5738
(*See our ad on page 691.*)

Alexor Inc. 7161 E. 87th St. Indianapolis, IN 46256 317-578-9111 fax, 317-578-9111

Alfa Laval Separation Inc. 955 Mearns Rd. Warminster, PA 18974-0556 215-443-4000 fax, 215-443-4112

Alfa Laval Thermal Inc. 5400 International Trade Dr. Richmond, VA 23231 804-222-5300 fax, 804-236-1303

All-Flo Pump Co. 9321 Pineneedle Dr. Mentor, OH 44060 440-354-1700 fax, 440-354-9466

Alliance Mfg. Inc. 1368 Capital Dr., P.O. Box 2006 Fond du Lac, WI 54936-2006 920-922-8100 800-969-7960 fax, 920-922-9500

Allied-Hunter Corp. 428 Pennsylvania Ave. Ft. Washington, PA 19034-3406 215-646-4700 800-887-6633 fax, 215-628-4040
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Allied UniKing Corp. Inc. 4750 Cromwell Ave., P.O. Box 18484 Memphis, TN 38118 901-365-7240 fax, 901-365-7306

AlliedSignal Inc., Fluorine Products 101 Columbia Rd. Morristown, NJ 07962 973-455-2763 800-631-8138 fax, 973-455-6300

Almco Inc. 507 W. Front St. Albert Lea, MN 56007 507-377-2102 800-521-2740 fax, 507-377-0451

Alpha Metals Inc. 600 Route 440 Jersey City, NJ 07304 201-434-6778 800-367-5460 fax, 201-434-7508

Alter Mfg. & Consulting Associates 26 St. Andrews Cir. Southampton, NY 11968 631-283-6117 fax, 631-283-1974

Altos Engineering Inc. 6009 N. 61st Ave. Glendale, AZ 85301 602-921-8434 fax, 602-937-6396

Amax Metals Recovery Inc., Subsidiary of Amax Metals Inc. Route 1, P.O. Box 160 Braithwaite, LA 70040 504-682-2341 fax, 504-682-4855

Ambar Environmental Products 4304 Firestone Rd. Metairie, LA 70001 504-733-7303 888-564-5667 fax, 504-733-8325

Ameracar Inc. 6216 Wilfrid Hamel Blvd., W. Quebec City, Que. G2E 2H7, Canada 418-877-5797 fax, 418-877-4383

American Allsafe Co. 99 Wales Ave. Tonawanda, NY 14150-5104 716-695-8311 800-231-1332 fax, 716-693-4589

American Chemical & Equipment P.O. Box 7 Ingleside, IL 60041 708-531-9199 800-734-2436 fax, 708-531-1978
(*See our ad on page 331.*)

American Chemical Products Corp. 5041 W. 161st St. Cleveland, OH 44142 216-267-7722 fax, 216-267-7721

American Lining Corp. 5940 Reeds Rd. Mission, KS 66202 913-362-9400 800-255-6245 fax, 913-262-1234
(*See our ad on page 680.*)

American Minerals Inc. 901 E. 8th Ave., Ste. 200 King of Prussia, PA 19406 215-962-5050 fax, 215-962-5056

American Nukem Corp. 1200 MacArthur Blvd. Mahwah, NJ 07430 201-818-0900 fax, 201-818-0038

American Plating Systems, Div. of Stewart Technologies Inc. 3342 E. Wier St. Phoenix, AZ 85040 602-232-0075 fax, 602-232-6076

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American Sigma 11601 Maple Ridge Rd., P.O. Box 820 Medina, NY 14103 716-798-5580 800-635-4567 fax, 716-798-5599

American Wire & Cathode Corp. 25504 John R. Rd. Madison Heights, MI 48071 248-399-8817 fax, 248-399-8817

AmeriChem Engineering Services 3430 E. Broadway Phoenix, AZ 85040-2832 602-437-1188 fax, 602-437-4860

Americraft Co. Inc. P.O. Box 2500 Palmetto, FL 34220-2500 800-237-3984 fax, 941-723-2452

Ameritest and Research Co. Inc. 5475 Perkins Rd. Bedford Heights, OH 44146 216-786-1403 800-280-8378 fax, 216-786-1426

Ames Metal Products Co. 4323 S. Western Blvd. Chicago, IL 60609-3086 773-523-3230 800-255-6937 fax, 773-523-3854
(*See our ad on page 317.*)

Ametek, Chemical Products Div. 900 Greenbank Rd. Wilmington, DE 19808 302-995-0400 800-441-7777 fax, 302-995-0491

Ametek, Plymouth Products Div. 502 Indiana Ave., P.O. Box 1047 Sheboygan, WI 53082-1047 920-457-9435 800-645-5426 fax, 920-457-6652

Ametek Rotron 75 North St., Sawyer Industrial Park Saugerties, NY 12477 914-246-3401 800-431-6033 fax, 914-246-3802

Amity Ltd. 498 S. Belvoir Blvd. Cleveland, OH 44121 216-382-2032 fax, 216-291-5949

An-Kor Plating Rack Co. Inc. 5238 S. 13th St. Milwaukee, WI 53221 414-282-6380 fax, 414-282-6309

Anachem Laboratories 1724 W. 58th St. Los Angeles, CA 90062 213-294-1262 fax, 213-294-3267

Analytical Measurements Inc. 621 Ramsey Ave. Hillside, NJ 07205 908-964-8686 800-635-5580 fax, 908-964-6622
(*See our ad on page 601.*)

Andco Environmental Processes Inc. 595 Commerce Dr., Audubon Industrial Park Amherst, NY 14228 716-691-2100 fax, 716-691-2880

Anderson Products Inc., Subsidiary of Wilton Corp. 1040 Southbridge St. Worcester, MA 01610 508-755-6100 fax, 800-729-4694

Andersons 480 W. Dussel Dr., P.O. Box 119 Maumee, OH 43537 419-893-5050 800-537-3370 fax, 419-893-6539

Andreae Filter P.O. Box 2538 Ardmore, OK 73402 800-891-9785 fax, 580-226-8189

Anode Products Co. Inc. 9425 Seymour Ave. Schiller Park, IL 60176 847-671-5550 800-255-7224 fax, 847-671-2883
(*See our ad on page 719.*)

Anode Systems 18030 Bariger South Bend, IN 46637 800-236-6701 fax, 219-271-6867

Anodic Inc. Route 111 Stevenson, CT 06491 203-268-9966 fax, 203-452-1893

Anomet Products Inc. 830 Boston Tpk. Shrewsbury, MA 01545 508-842-3069 fax, 508-842-0847

Ansimag Inc. 1090 Pratt Blvd. Elk Grove Village, IL 60007 847-290-0482 fax, 847-290-0481

Apex Rack and Coating Co. 739 Cottage Grove, S.E. Grand Rapids, MI 49507 616-452-3139 fax, 616-452-9970

Apple Fabrication Co. 815 Mercury Ave. Duncanville, TX 75137 972-298-9898 800-926-6725 fax, 972-298-8474
(*See our ad on page 675.*)

Applied Surface Technologies 15 Hawthome Dr. New Providence, NJ 07974 908-464-6675 fax, 908-464-7475

Applied Technical Services Inc. 1190 Atlanta Industrial Dr. Marietta, GA 33006 770-423-1400 fax, 770-424-6415

Applied Thermal Technologies Inc., Hydro-Miser Div. 548 S. Pacific St., Ste. B-101, P.O. Box 1900 San Marcos, CA 92079-1900 760-744-5083 800-736-5083 fax, 760-744-5031
(*See our ad on page 640.*)

Aqua Care Systems Inc., Filtration Systems Div./Metering Pump Group 9545 Hardpan Rd. Angola, NY 14006 716-549-2500 fax, 716-549-6250

Aqua-Chem Inc., Water Technologies Div. 7800 N. 113th St., P.O. Box 421 Milwaukee, WI 53201 414-359-0600 fax, 414-577-2723

Aqualogic Inc. 30 Devine St. North Haven, CT 06473 203-248-8959 800-989-8959 fax, 203-288-4308
(*See our ad on page 821.*)

Aqualytics, Div. of Graver Co. 7 Powder Horn Dr. Warren, NJ 07059 732-563-2800 fax, 732-563-2816

Aquametrix Inc. 4-30 Royal Crest Ct. Markham, Ont. L3R 9W8, Canada 905-946-1064 fax, 905-946-8064

Aqueous Recovery Resources Inc. 300 Adams St. Bedford Hills, NY 10507 914-241-2827 fax, 914-242-7346

Arbonite, Div. of P&R Industries 3826 Old Easton Rd. Doyleston, PA 18901 215-348-2950 800-424-4978
(*See our ad on page 669.*) **fax, 215-345-1251**

Arcal Chemicals Inc. 223 Westhampton Ave. Capital Heights, MD 20743 301-336-9300 800-638-2672 fax, 301-336-6597

Arconium Corp. 50 Sims Ave. Providence, RI 02909 401-456-0800 800-343-0282 fax, 401-421-2419
(*See our ad on page 265.*)

Argon-Rhodium Inc. 2980 W. Shore Rd. Warwick, RI 02886 401-738-4404 fax, 401-738-4765

Armstrong Engineering Associates Inc. P.O. Box 566 West Chester, PA 19381-0566 610-436-6080 fax, 610-436-0374

Artcraft Welding Specialty Inc. 861 McGlincey Ln. Campbell, CA 95008 408-377-2725 fax, 408-377-2677

Asahi Glass America Inc. 450 Lexington Ave. New York, NY 10017 212-764-3155 fax, 212-687-4600

Asahi/America Inc. 35 Green St., P.O. Box 653 Malden, MA 02148 781-321-5409 800-343-3618 fax, 781-321-4421
(*See our ad on page 723.*)

Ashland Chemical Co., Div. of Ashland Inc. P.O. Box 2219 Columbus, OH 43216 614-790-3333 800-894-5549 fax, 614-790-3465

Ashley Labs 10030 Harford Rd., P.O. Box 8419 Baltimore, MD 21234 410-668-1270 fax, 410-668-0668

Asoma Instruments Inc., Spectro Analytical Instruments Group 1611 Headway Cir., Bldg. 3 Austin, TX 78754 512-258-6608 800-580-6608 fax, 512-331-9123
(*See our ads on pages 525, 575.*)

Asoma-TCI 795 Wurlitzer Dr. North Tonawanda, NY 14120 716-692-8855 800-777-8946 fax, 716-692-3265

Asset Exchange Ltd. 3502 E. Broadway Rd. Phoenix, AZ 85040 602/437-1188 fax, 602-437-4860

Associated Rack Corp. 225 W. Ohio St., Ste. 600 Chicago, IL 60610 312-595-9076 888-675-5000 fax, 312-595-9079
(*See our ad on page 705.*)

AstroCosmos Metallurgical Inc. 835 Flynn Rd. Camarillo, CA 93012-8702 805-482-9825 800-350-9825 fax, 805-482-2923
(*See our ad on page 763.*)

Atcor Corp. 150 Great Oaks Blvd. San Jose, CA 95119-1367 408-629-6080 fax, 408-629-9009

Atlantech Process Technology Inc. 5579B Chamblee Dunwoody Rd., Ste. 161 Atlanta, GA 30328 770-390-0085 fax, 770-390-0129

Atlas Electric Devices Co. 4114 N. Ravenswood Ave. Chicago, IL 60613 773-327-4520 fax, 773-327-5787

Atlas Minerals & Chemicals Inc. 1227 Valley Rd., P.O. Box 38 Mertztown, PA 19539-0038 610-682-7171 800-523-8269 fax, 610-682-9200

Atlas Technicast Ltd. 8550 Aetna Rd. Cleveland, OH 44105 216-441-6155 800-318-5064 fax, 216-441-5270

Atomergic Chemetals Corp. 222 Sherwood Ave. Farmingdale, NY 11735 631-694-9000 fax, 631-694-9177

Atotech USA Inc. 1750 Overview Dr., P.O. Box 12000 Rock Hill, SC 29731-2000 803-817-3500 800-752-8464 fax, 803-817-3666

Atotech USA Inc. 20026 Progress Dr. Strongsville, OH 44136 440-572-7800 800-433-8336 fax, 440-572-7820
(*See our ads on pages 11, 345, 351, 591, 635.*)

Atramet Inc. 222 Sherwood Ave. Farmingdale, NY 11735-1718 631-694-9000 fax, 631-694-9177

Aubin Co., A.E. 345 N. Main St., P.O. Box 456 Marlborough, CT 06447 860-295-9597 800-423-0697 fax, 860-295-8962

Auromet Corp. 37 Chasner St. Hempstead, NY 11550 516-538-4515 fax, 516-483-1731

Automate Tech Inc. 4711 126th Ave. N., Ste. J Clearwater, FL 33762 727-572-7474 fax, 727-572-8073
(See our ad on page 802.)

Automated Finishing Inc. N60 W14521 W. Kaul Ave. Menomonee Falls, WI 53051 414-252-4646 800-553-5122 fax, 414-252-3056

Automation Products Inc. 3030 Max Roy St. Houston, TX 77008-6294 713-869-0361 800-231-2062 fax, 713-869-7332

Automation U.S.A. 56 W. Winter St., P.O. Box 563 Westminster, MD 21158 410-857-3819 800-678-4370 fax, 410-857-3818
(See our ad on page 579.)

B

B&M Plastics Inc. 511 York Ave. Pawtucket, RI 02861 401-728-0404 fax, 401-728-1790

B&P Plating Supply, Div. of Behrens & Peatman 74 Broderick Rd. Bristol, CT 06010 860-589-5799 fax, 860-589-9163
(See our ad on page 347.)

BASF Corp., Chemicals Div. 3000 Continental Dr. N. Mt. Olive, NJ 07828-1234 973-426-2600 800-669-2273 fax, 973-426-4752

BEWT Systems Inc. P.O. Box 6932 Chesterfield, MO 63006 314-527-1022 fax, 314-527-8606

BF Services 5265 Gravelbrook Dr. Richmond, VA 23234 804-271-0050 fax, 804-271-0725

BFGoodrich Co., Corzan Industrial Systems Div. 9911 Brecksville Rd. Cleveland, OH 44141-3247 216-447-5000 800-331-1144 fax, 216-447-5750

BJM Corp. 123 Spencer Plains Rd., P.O. Box 1138 Old Saybrook, CT 06475 860-399-5937 800-442-2562 fax, 860-399-7784

BKTS Inc. 1369 S. Main St. Meadville, PA 16335 814-724-7160 877-724-2587 fax, 814-333-4169
(See our ad on page 705.)

BOC Gases 575 Mountain Ave. Murray Hill, NJ 07974 908-464-8100 800-932-0803 fax, 908-779-9015

BVS Inc. Route 322 W. & Poplar Rd. Honey Brook, PA 19344 610-273-2841 fax, 610-273-2843

Baker Co., M.E. 25 Wheeler St. Cambridge, MA 02138 617-547-5460 800-963-2269 fax, 617-354-7396

Baker Technology Associates Inc. 710 Wilshire Blvd., Ste. 610 Santa Monica, CA 90401 310-458-1752 fax, 310-458-1065

Balzers Materials 25 Sagamore Park Rd. Hudson, NH 03051 603-594-1500 800-248-7073 fax, 603-595-3234

Barnant Co. 28 W. 092 Commercial Ave. Barrington, IL 60010 847-381-7050 800-637-3739 fax, 847-381-7053
(See our ads on pages 601, 745.)

Baron Blakeslee Inc. 1905 Mines Rd. Pulaski, TN 38478 931-363-4160 800-548-4422 fax, 931-424-3709

Barrett Centrifugals Inc. P.O. Box 15059 Worcester, MA 01615-0059 508-755-4306 800-228-6442 fax, 508-753-4805

Bayer Corp., Industrial Chemicals Div. 100 Bayer Rd. Pittsburgh, PA 15205-9741 412-777-2000 800-645-3749 fax, 412-777-4109

Beaver Industries Inc. Trimex Bldg., Route 11 Mooers, NY 12958 518-236-5489 fax, 518-236-5433

Beckart Environmental Inc. 6900 46th St. Kenosha, WI 53144 262-656-7680 fax, 262-656-7699
(See our ad on page 802.)

Becker Bros. Carbon Corp. 3450 S. Laramie Cicero, IL 60804 773-242-1260 fax, 773-242-1023
(See our ad on page 369.)

Bel Air Finishing Supply Inc. 110 Byfield St. Warwick, RI 02888 401-781-4408 fax, 401-781-4498

Belanger Inc. 1001 Doheny Ct. Northville, MI 48167 248-349-7010 fax, 248-349-2309

Belding Tank Technologies Inc. P.O. Box 160M Belding, MI 48809 616-794-1130 800-253-4252 fax, 616-794-3666
(See our ad on page 673.)

Belke Mfg. Co. 950 N. Cicero Ave., P.O. Box 31854 Chicago, IL 60651 773-626-4606 fax, 773-626-2223
(See our ads on pages 707, 709.)

Belmont Metals Inc. 330 Belmont Ave. Brooklyn, NY 11207-4000 718-342-4900 fax, 718-342-0175
(See our ad on page 329.)

Beltservice Corp. 4143 Rider Trail, N. Earth City, MO 63045 314-344-8555 800-727-2358 fax, 314-344-8511

Benchmark Inc. 4660 13th St. Wyandotte, MI 48192 734-285-0900 800-521-9107 fax, 734-285-4236

Benchmark Products Inc. 5425 W. 84th St., P.O. Box 68809 Indianapolis, IN 46268 317-875-0051 800-428-0719 fax, 317-872-0248
(See our ad on page 273.)

Beta Control Systems Inc. 6950 S.W. 111th Ave. Beaverton, OR 97005 503-646-3399 fax, 503-627-0888

Better Engineering Mfg. Inc. 8361 Town Center Ct. Baltimore, MD 21236-4964 410-931-0000 800-229-3380 fax, 410-931-0053

BetzDearborn, Div. of Hercules 4636 Somerton Rd. Trevose, PA 19053-6783 215-355-3300 800-775-7175 fax, 215-953-5524

Bex Inc. 37709 Schoolcraft Rd. Livonia, MI 48150-1009 734-464-8282 fax, 734-464-1988
(*See our ad on page 173.*)

Billco Mfg. Co. 100 Grandview Blvd. Zelienople, PA 16063-9799 412-452-7390 fax, 412-452-0217

Binary Process Solutions 2125 E. 5th St., #101 Tempe, AZ 85281 602-858-0897 fax, 602-829-3775

Bio-Recovery Systems Inc. 2001 Copper Ave. Las Cruces, NM 88005 505-523-0405 800-697-2001 fax, 505-523-1638

BioChem Systems 14452 W. 44th Ave. Golden, CO 80403 303-277-9700 800-777-7870

BioClean USA 60 Buttonwood St. Bristol, RI 02809 401-253-6090 fax, 401-253-6170

Birchwood Laboratories Inc. 7900 Fuller Rd. Eden Prairie, MN 55344 612-937-7931 800-328-6156 fax, 612-937-7979
(*See our ad on page 463.*)

Bison Corp. 1935 Allen Ave., S.E. Canton, OH 44707 330-455-0282 fax, 330-455-0285

Blast-It-All 185 Piper Ln., P.O. Box 1615 Salisbury, NC 28145 704-637-3300 800-535-2614 fax, 704-638-9311

Blue Spring Corp. 349 FM 3084 Port Lavaca, TX 77979 361-552-8898 fax, 361-552-4393
(*See our ad on page 837.*)

Blue Wave Ultrasonics 960 S. Rolff St., P.O. Box 4347 Davenport, IA 52808-4347 319-322-0144 800-373-0144 fax, 319-322-7180

Boride Products Inc. 2879 Aero Park Dr. Traverse City, MI 49686 231-946-2100 800-662-2131 fax, 231-946-3025

Bowden Industries Inc. 1004 Oster Dr., N.W. Huntsville, AL 35816 226-533-3700 800-553-3637 fax, 226-539-7917

Bran + Luebbe 1025 Busch Pkwy. Buffalo Grove, IL 60089 847-520-0700 fax, 847-520-0855

Brandywine Abrasives 705 General Washington Ave., Ste. 701 Norristown, PA 19403 610-630-8024 fax, 610-630-9730

Branson Ultrasonics Corp. 41 Eagle Rd. Danbury, CT 06813-1961 203-796-0400 fax, 203-796-0320

Braude (London) Ltd., E. Liberta House, Sandhurst, Camberley Surrey GU47 8JR, U.K. 44 1252 876123 fax, 44 1252 875281

Brawn Mixer Inc. 12764 Greenly St. Holland, MI 49424 616-399-5600 fax, 616-399-3084

Brent America Inc. 921 Sherwood Dr. Lake Bluff, IL 60044 847-295-1660 800-222-8819 fax, 847-295-8748

Brian Co. Ltd., M.A. 4500 N. Talbot Rd. Oldcastle, Ont. N9R 1L0,, Canada 519-737-1529 fax, 519-737-1647

Brinecell Inc. 2515 South 300 West Salt Lake City, UT 84115 801-487-2555 877-973-6400 fax, 801-487-6703

Brinkmann Instruments Inc. One Cantigue Rd., P.O. Box 1019 Westbury, NY 11590-0207 516-334-7500 800-645-3050 fax, 516-334-7506

Broco Products Inc. 18624 Syracuse Ave. Cleveland, OH 44110 216-531-0880 800-321-0837 fax, 216-531-8539

Bromley Inc., B.A. 340 Main St. Springfield, MA 01105 413-736-4280 fax, 413-737-4591

Brookline Machinery Inc. 100 Industrial Dr. Ivyland, PA 18974 215-364-5160 fax, 215-364-4465

Brooktronics Engineering Corp. 28231 Ave. Crocker, Bldgs. 60 & 70 Valencia, CA 91355 661-294-1195 800-394-0240 fax, 661-294-9032
(*See our ad on page 365.*)

Brulin Corp. P.O. Box 270 Indianapolis, IN 46206-0270 800-776-7149 fax, 317-925-4596

Buchholz Smith Plastic Fabrication Inc. HCR 64, P.O. Box 295 D1 West Plains, MO 65775 417-257-0778 fax, 417-256-0211

Buck Scientific 58 Fort Point St. E. Norwalk, CT 06855 203-853-9444 800-562-5566 fax, 203-853-0569

Buffalo Abrasives 960 Erie Ave. N. Tonawanda, NY 14120 716-693-3856 fax, 716-693-4092

Bulk Lift International Inc. 1013 Tamarac Carpentersville, IL 60110 847-428-6059 800-342-2247 fax, 847-428-7180

Bullard Co., E.D. 1899 Safety Way Cynphiana, KY 41031 606-234-6611 800-227-0423 fax, 606-234-1303

Burke Rack Inc. 589 W. Explorer St. Brea, CA 92621 714-529-6777 fax, 714-529-6942

Burlingham International 1032 W. 18th St., Unit A3 Costa Mesa, CA 92627-4556 714-645-1529 800-659-5506 fax, 714-645-2359

Burns & McDonnell 9400 Ward Pwy. Kansas City, MO 64114 816-822-3169 fax, 816-822-3513
(*See our ad on page 629.*)

Burt Process Equipment 1050 Sherman Ave. Hamden, CT 06514 203-287-1985 800-426-3856 fax, 203-288-7354

C

C&M Liner Co. Inc. 2374-B16 Stone Mountain/Lithonia Rd. Lithonia, GA 30058 770-482-9513 800-622-1128 fax, 770-482-5774

C&S Engineering Corp. 956 Old Colony Rd. Meriden, CT 06450 203-235-5727 800-272-2557 fax, 203-237-7498

CAE Alpheus Inc. 9119 Milliken Rancho Cucamonga, CA 91730 909-481-6444 fax, 909-980-5696

CAE Cleaning Technologies 4933 Provident Dr. Cincinnati, OH 45246-1020 513-870-6129 800-398-1159 fax, 513-870-1786
(*See our ad on page 163.*)

CAE Ransohoff Inc. 4933 Provident Dr. Cincinnati, OH 45246-1020 513-870-0100 800-248-9274 fax, 513-870-0105

CAE Ultrasonics 9 N. Main St., P.O. Box 220 Jamestown, NY 14702-0220 716-665-2340 800-766-6606 fax, 716-665-2480

CB Mills, Div. of Chicago Boiler 1300 Northwestern Ave. Gurnee, IL 60031-2348 847-662-4000 800-522-7343 fax, 847-662-4003

CDF Corp. 77 Industrial Park Rd. Plymouth, MA 02360 508-747-5858 800-443-1920 fax, 508-747-6333

CDS Environmental Services 293 Sanders Rd. Barrie, Ont. L4N 9A3,, Canada 705-725-6262 fax, 705-725-0036

CH2M Hill 1380 Corporate Center Curve, Ste. 200 Eagan, MN 55121 651-688-8100 fax, 651-688-8844

CIMID 50 S. Center St. Orange, NJ 07050 973-672-5000 800-552-4643 fax, 973-672-0059

CMI International Corp. 945 Busse Rd. Elk Grove Village, IL 60007-6098 847-439-4404 800-678-1117 fax, 847-439-4425
(*See our ad on page 567.*)

CNA Insurance Cos. CNA Plaza Chicago, IL 60685 312-822-3987 800-262-6241 fax, 312-822-2418

CP/PhibroChem, Div. of Philipp Brothers Chemicals Inc. 1 Parker Plaza Fort Lee, NJ 07024 201-944-6020 fax, 201-944-7911
(*See our ad on page 237.*)

CRC Industries Inc. 885 Louis Dr. Warminster, PA 18974 215-674-4300 fax, 215-674-2196

CS Unitec P.O. Box 7690 Wilton, CT 06897 203-853-9522 800-700-5919 fax, 203-853-9921

CSC Scientific Co. Inc. 2810 Old Lee Hwy. Fairfax, VA 22031 703-876-4030 800-458-2558 fax, 703-280-5142

CTI Ancor 2121 San Jacinto St., Ste. 2500 Dallas, TX 75201 214-953-4687 fax, 214-953-4685

CTI-Cryogenics Div., Helix Technology Corp. Mansfield Corporate Center, Nine Hampshire St. Mansfield, MA 02048 508-337-5000 800-284-2796 fax, 508-337-5169

CVC Products Inc. 525 Lee Rd. Rochester, NY 14606 716-458-2550 fax, 716-458-0424

CVI, Div. of Process Systems International P.O. Box 2138 Columbus, OH 43216 614-876-7381 800-828-7381 fax, 614-876-5648

Caledon Controls Ltd. 2410 Tedlo St., Unit #1 Mississauga, Ont. L5A 3V3,, Canada 905-949-2739 fax, 905-949-2766

Calfran International Inc. 52-54 Wayside Ave., P.O. Box 269 Springfield, MA 01101 413-732-3616 fax, 413-732-9246

Calgon Corp. P.O. Box 1346 Pittsburgh, PA 15230-1346 412-494-8000 800-955-0090 fax, 412-494-8927

Callery Chemical Co. P.O. Box 429 Pittsburgh, PA 15230 412-538-3510 fax, 412-967-4188

Camac Industries 18 Gail Ct. Sparta, NJ 07871 973-300-5575 fax, 973-300-5576
(*See our ad on page 743.*)

Camel Grinding Wheels 7530 N. Caldwell Ave. Niles, IL 60714 847-647-5994 800-447-4248 fax, 847-647-1861

Can-Eng Mfg. Ltd. P.O. Box 235 Niagara Falls, NY 14302 905-356-1327 fax, 905-356-3375

Canadian Finishing Systems Ltd. 3455 Harvester Rd. Burlington, Ont. L7N 3P2,, Canada 905-634-5168 fax, 905-634-5699

Canfield Technologies Inc. 1 Crossman Rd. Sayreville, NJ 08872 732-316-2100 800-526-4577 fax, 732-316-2177

Capaccio Environmental Engineering Inc. 75 Union Ave. Sudbury, MA 01776 978-443-0202 fax, 978-443-0366

Capital Controls Co. Inc. 3000 Advance Ln., P.O. Box 211 Colmar, PA 18915 215-997-4000 800-523-2553 fax, 215-997-4062

Capsule Environmental Engineering Inc. 1970 Oakcrest Ave., Ste. 215 St. Paul, MN 55113 612-636-2644 800-328-8246 fax, 612-636-3106

Carborundum Abrasive Co. P.O. Box 350 Niagara Falls, NY 14304 716-731-7777 fax, 716-731-9697

Carbtrol Corp. 51 Riverside Ave. Westport, CT 06880 203-226-5642 800-242-1150 fax, 203-226-5322

Carlson Erie Corp. 1115 Cherry St. Erie, PA 16501 814-455-2768 fax, 814-454-3979

Carolinch Co. 1025 Louis Dr. Warminster, PA 18974 215-674-0379 fax, 215-674-2538

Carpenter Chemicals LC 206 N. Washington St., Ste. 330 Alexandria, VA 23214 703-683-3037 fax, 703-683-4131

Carson Mfg. Co. 1300 Dynamic St., P.O. Box 750338 Petaluma, CA 94975 707-778-3141 800-423-2380 fax, 707-778-8691
(*See our ad on page 675.*)

Carver Pump Co. 2415 Park Ave. Muscatine, IA 52761 319-263-3410 fax, 319-263-4565

Castion Corp. 290 Moody St. Ludlow, MA 01056-1244 413-589-1601 800-628-7528 fax, 413-589-7301
(*See our ad on page 819.*)

Castrol Industrial North America 1001 W. 31st St. Downers Grove, IL 60515 630-241-4000 fax, 630-241-1977

Cataphote Co. P.O. Box 2369 Jackson, MS 39225 601-939-4612 800-221-2575 fax, 601-932-5339

Catho-Pin Products 24350 John R. Hazel Park, MI 48030 248-548-7795 fax, 248-548-5288
(*See our ad on page 357.*)

Catholyte Inc. 646 Terrace Dr. Paramus, NJ 07652 201-262-8544 fax, 201-262-5509

Ceco Filters Inc. 1029 Conshohocken Rd., P.O. Box 683 Conshohocken, PA 19428 610-825-8585 800-220-8021 fax, 610-825-3108

Ceilcote Air Pollution Control 14955 Sprague Rd., Ste. 250 Strongsville, OH 44136 440-243-0700 fax, 440-243-9854

Cemco International Inc., A Div. of Vanguard Holdings 239 St. Nicholas Ave. S. Plainfield, NJ 07080 908-756-6755 fax, 908-753-6540

Cerac Inc. P.O. Box 1178 Milwaukee, WI 53201-1178 414-289-9800 fax, 414-289-9805

Champion Laboratories Inc. 200 S. 4th St. Albion, IL 62806-1313 618-445-6011 fax, 618-445-4040

Chem Lab Supplies 1060 Ortega Way Placentia, CA 92870 714-630-7902 fax, 714-630-3553

Chem-Tainer Industries 361 Neptune Ave. N. Babylon, NY 11704 631-661-8300 800-645-5607 fax, 631-661-8209

Chema Technology Inc. P.O. Box 51616 New Berlin, WI 53151-0616 414-524-8006 fax, 414-524-8131

Chemat Technology Inc. 19365 Business Center Dr., Ste. 8-9 Northridge, CA 91324 818-727-9786 fax, 818-727-9477

Chemcut Equipment Group, Atotech USA Inc. 500 Science Park Rd. State College, PA 16803 814-238-0514 800-553-3695 fax, 814-238-6427

Chemical Equipment Fabricators Ltd. 26 Riviera Dr. Markham, Ont. L3R 5M1, Canada 416-438-9266 fax, 416-438-0382

Chemical Solvents Inc. 3751 Jennings Rd. Cleveland, OH 44109 216-741-9310 800-362-0693 fax, 216-741-4080

Chemineer Inc., A Unit of Robbins & Myers 125 Flagship Dr. N. Andover, MA 01845 978-687-010100 800-643-0641 fax, 978-687-8500

Chemithon Surface Finishing Inc. 5430 W. Marginal Way S.W. Seattle, WA 98106-1598 206-937-9954 fax, 206-932-3786

Chemtech Finishing Systems Inc. 23177 Commerce Dr. Farmington Hills, MI 48335 248-478-5200 800-791-3118 fax, 248-478-6810

Chemtech Products Inc. 1655 Des Peres Rd, Ste. 210 St. Louis, MO 63131 314-965-7100 800-325-3332 fax, 314-966-2907

Chemtronics 8125 Cobb Center Dr. Kennesaw, GA 30152-4386 770-424-4888 fax, 770-424-4267

Chiron America 14201 G. S. Lakes Dr. Charlotte, NC 28273 704-587-9526 fax, 704-587-0485

Chlorinators Inc. 4125 S.W. Martin Hwy., Ste. 2 Palm City, FL 34990 561-288-4854 800-327-9761 fax, 561-287-3238

Chromalox 701 Alpha Dr. Pittsburgh, PA 15238 412-967-3800 fax, 412-967-5148

ChromeTech Inc. P.O. Box 295 Windsor, OH 44099 216-968-9820 fax, 216-968-9822

Church & Dwight Co. Inc. 469 N. Harrison St. Princeton, NJ 08543-5297 609-683-5900 800-221-0453 fax, 609-497-7176

Cianflone Scientific Instruments Corp. 228 RIDC Park West Dr. Pittsburgh, PA 15275-1002 412-787-3600 800-569-9400 fax, 412-787-5022

Cincinnati Industrial Machinery, Div. of Eagle Picher Industries Inc. 3280 Hageman St. Cincinnati, OH 45241 513-769-0700 fax, 513-769-0697

Circle-Prosco Inc. 2017 Yost Ave. Bloomington, IN 47403 812-339-3653 fax, 812-331-2566

Circuit Chemistry Equipment 7140 Madison Ave., W. Golden Valley, MN 55427 612-591-0297 fax, 612-591-1861
(*See our ad on page 641.*)

Ciscan Industries Ltd. 5918 Roper Rd. Edmonton, Alb. T6B 3E1, Canada 780-466-3178 800-661-8529 fax, 780-468-5904

Clariant Corp. 4000 Monroe Rd. Charlotte, NC 28205 704-331-7000 fax, 704-331-7109
(*See our ad on page 483.*)

Clawson Tank Co. 4545 Clawson Tank Dr. Clarkston, MI 48346 248-625-8700 fax, 248-625-3066

Clayton Environmental Consultants Inc. 41650 Gardenbrook Rd., Ste. 155 Novi, MI 48375 810-344-8550 fax, 810-344-0229

Clearclad Coatings Inc. 16910 S. Lathrop Ave. Harvey, IL 60426 708-596-0001 fax, 708-596-0734

Clemco Industries Corp., Zero Products Div. One Cable Car Dr. Washington, MO 63090 314-239-8135 fax, 314-239-0788

Cleveland Black Oxide 836 Broadway Ave. Cleveland, OH 44115 216-861-4431 fax, 216-861-0711

Cleveland Process Corp. 127 S.W. 5th Ave. Homestead, FL 33030 305-248-4312 800-241-0412 fax, 305-248-4371
(*See our ad on page 759.*)

Clinton Power, Subsidiary of Benjamin Power Co. 611 Landwehr Rd., P.O. Box 1597 Northbrook, IL 60062 847-498-4200 fax, 847-498-9944
(*See our ad on page 687.*)

Codman Co., F.L. & J.C. 185 Plain St. Rockland, MA 02370 781-878-1000 fax, 781-878-4709

Cognis Inc. 2330 Circadian Way Santa Rosa, CA 95407 707-526-6225 800-524-3307 fax, 707-575-7833

Colloid Environmental Technologies Co., Subsidiary of American Colloid 1350 W. Shure Dr. Arlington Heights, IL 60004-1440 847-392-5800 800-527-9948 fax, 847-506-6150

Columbia Chemical Corp. 3097 Interstate Pkwy. Brunswick, OH 44212-4328 330-225-3200 fax, 330-225-1499
(*See our ad on page 324.*)

Columbine International Ltd. 5441 Merchant Cir. Placerville, CA 95667 530-622-2791 800-635-6693 fax, 530-622-2704

Comco Inc. 2151 N. Lincoln St. Burbank, CA 91504 818-841-5500 800-796-6626 fax, 818-955-8365

Comdel 11 Kondelin Rd. Gloucester, MA 01930 978-282-0620 fax, 978-282-4980

Commodore Separation Technologies Inc. 3240 Town Point Dr., Ste. 200 Kennesaw, GA 30144 770-422-1518 fax, 770-422-1163

Commonwealth Scientific Corp. 500 Pendleton St. Alexandria, VA 22314 703-548-0800 fax, 703-548-7405

Competition Chemicals Inc. 715 Railroad St., P.O. Box 820 Iowa Falls, IA 50126 515-648-5121

Complete Filtration 1776D W. Clarkston Rd. Lake Orion, MI 48362 810-693-0500 fax, 810-693-0503

Compliance Systems Inc. 18 Marin Way Exeter, NH 03833 603-772-7755 fax, 603-772-9944

Compliance Systems International 1029 Conshohocken Rd. Conshohocken, PA 19428 610-825-8585 800-220-8021 fax, 610-825-3108

Composite Structures International. Inc. (CSI) 4115 Keller Springs Rd., Ste. 224 Dallas, TX 75244 972-250-1633 800-345-5636 fax, 972-250-1530

Composition Materials Co. Inc. 1375 Kings Hwy., E. Fairfield, CT 06430 203-384-6111 800-262-7763 fax, 203-335-9728

Concord Resources Group Inc. 5299 DTC Blvd., Ste. 1100 Englewood, CO 80111 303-267-1800 fax, 303-773-2205

Conserve Engineering Co. LLC 303 Broadway, Ste. 212 Laguna Beach, CA 92651 949-494-6440 fax, 949-494-9918
(*See our ad on page 783.*)

Consolidated Engineering Co. 2871 McCollum Pkwy., N.W. Kennesaw, GA 30144-3651 770-422-5100 fax, 770-422-6968

Consolidated Mfg. of Pittsburgh (CMP) 1424 Barnsdale St. Pittsburgh, PA 15217 412-421-0991 800-824-6084 fax, 412-421-0991

Contact Rubber Corp. 8635 198th Ave., P.O. Box 97 Bristol, WI 53104 414-857-2361 fax, 414-857-9483

Contaminant Recovery Systems Inc. 9 Rocky Hill Rd. Smithfield, RI 02917 401-231-3770 fax, 401-231-3360
(*See our ads on pages 725, 811, 835.*)

Continental Surface Treatment Inc. 6801 Engle Rd., Ste. J Middleburg Hts., OH 44130-7930 440-239-9710 888-278-8732 fax, 440-239-9705
(*See our ad on page 509.*)

Controlled Power Co. 1955 Stephenson Hwy. Troy, MI 48083 248-528-3700 800-521-4792 fax, 248-528-0411
(*See our ad on page 693.*)

Cooley Wire Products Mfg. Co. 5025 N. River Rd. Schiller Park, IL 60176 847-678-8585 fax, 847-678-8612
(*See our ads on pages 635, 713.*)

Cooling Technology Inc. 1800 Orr Industrial Ct. Charlotte, NC 28213 704-596-4109 800-872-1448 fax, 704-597-8697
(*See our ad on page 640.*)

Coral Chemical Co. 135 LeBaron St. Waukegan, IL 60085 847-336-8100 800-228-4646 fax, 847-336-8518

Corfin Inc. 7B Raymond Ave. Salem, NH 03079 603-893-9900 fax, 603-893-6800

Cornerstone Systems Inc. 800 McHenry Ave., Ste. B Crystal Lake, IL 60014 815-356-8110 800-275-4274 fax, 815-356-8156

Corning Inc. MP-21-4/P.O. Box 56 Corning, NY 14830 607-974-7201 fax, 607-974-7203

Corode B.V. P.O. Box 854 5280 AV, Boxtel, Netherlands 31 4116 85977 fax, 31 4116 86067

Corpane Industries Inc. 10100 Bluegrass Pkwy. Louisville, KY 40299 502-491-4433 fax, 502-491-9944

Corpex Technologies Inc. 5400 Miami Blvd. Morrisville, NC 27560 919-941-0847 fax, 919-941-0652

Corrosion Technology Inc. 620 Hinkle St., P.O. Box 10386 Green Bay, WI 54307 920-499-1632 fax, 920-499-2554

Corrotec Inc. 1125 W. North St. Springfield, OH 45504 937-325-3585 fax, 937-325-9456

Covo Corp. P.O. Box 49076 Sarasota, FL 34230-6076 941-753-9539

Covofinish Co. Inc. P.O. Box 478 Harmony, RI 02829-0478 401-568-9191 fax, 401-568-9196

Crane Co., Chemppump Div. 175 Titus Ave. Warrington, PA 18976 215-343-6000 fax, 215-343-3873

Crest Ultrasonics Corp. 1 Scotch Rd., P.O. Box 7266 Trenton, NJ 08628 609-883-4000 800-394-4057 fax, 609-883-6452
(*See our ad on page 165.*)

Cuda Corp. 93 Industrial Airpark Calumet, MI 49913 906-482-1600 800-780-2832 fax, 906-482-3344

Cuno Inc. 400 Research Pkwy. Meriden, CT 06450 203-237-5541 800-243-6894 fax, 203-238-8977

Cuno Separations, Systems Div. 50 Kerry Pl. Norwood, MA 02062 617-769-6112 800-367-6805 fax, 617-769-3274

Cure International Inc. 1001 U.S. Highway One Jupiter, FL 33477 561-575-3500 fax, 561-575-9510

Curtin-Hebert Co. Inc. 11 Forest St., P.O. Box 511 Gloversville, NY 12078 518-725-7157 fax, 518-773-3805

Custom Scientific Instruments 13 Wing Dr. Cedar Knolls, NJ 07927 973-538-8500 fax, 973-984-6793

Cyanide Destruct Systems Inc. 383 Elmira Rd. Guelph, Ont. N1K 1H3, Canada 519-837-1899 fax, 519-837-1622

Cyclone Pumps 5181 113th Ave., N. Clearwater, FL 34620 727-572-9867 fax, 727-573-9198

D

DC Products 32550 Central Ave Union City, CA 94587 510-487-5823

DCE Inc. 11301 Electron Dr. Jeffersontown, KY 40299 502-267-0707 800-767-0702 fax, 502-267-3074

DEC International, Engineered Products Group 1919 S. Stoughton Rd. Madison, WI 53716 608-222-3484 800-626-3111 fax, 608-222-7255

DMP Corp. 18 Tidal Way, P.O. Box 1088 Fort Mill, SC 29716 803-548-0853 800-845-3681 fax, 803-548-3590
(*See our ad on page 799.*)

DSM Fine Chemicals Park 80 West, Plaza II, 4th Fl. Saddle Brook, NJ 07663-5812 201-845-4404 fax, 201-845-4406

Dagex Inc. 4141 Yonge St., Ste. 307 North York, Ont. M2P 2A8, Canada 416-250-7111 800-665-7136 fax, 416-250-8111

Dan Technology 25030 Coccaglio Brescia, Italy 39 030 772 1850 fax, 39 030 724 0612
(*See our ad on page 37.*)

Danglers Inc. 35 Oakdale Ave. Johnston, RI 02919 401-274-7742 fax, 401-274-7742
(*See our ad on page 345.*)

Darly Custom Technology Inc. 121 W. Dudley Town Rd. Bloomfield, CT 06002-0067 860-243-5518 fax, 860-286-0162

Darmann Abrasive Products 56 Sterling St., Bldg. 10, P.O. Box 55 Clinton, MA 01510 978-365-4544 fax, 978-365-3839

Darrah Electric Co. 5914 Merrill Ave. Cleveland, OH 44102-5699 216-631-0912 800-621-0014 fax, 216-631-0440
(*See our ad on page 693.*)

Davidoff, Charles 5 Secatoag Ave. Port Washington, NY 11050 516-883-3700

Dawn Electrochemical Engineering 84 Jay Dr. Madison, AL 35758 205-830-1530 fax, 205-430-0509

Dayton Water Systems 1288 McCook Ave. Dayton, OH 45404 937-461-5225 800-424-9250 fax, 937-461-0308

De Nora North America Inc. 39 Veronica Ave. Somerset, NJ 08873 732-545-5100 800-762-2101 fax, 732-545-5170
(*See our ad on page 249.*)

Deburring & Surface Finishing Research Laboratory Marquette University, 1515 W. Wisconsin Ave. Milwaukee, WI 53233 414-288-7259 fax, 414-288-7082

Deburring Laboratories 365 John Downey Dr. New Britain, CT 06051 860-225-8767 fax, 860-225-2472

Dedeco International Inc. Route 97 Long Eddy, NY 12760 914-887-4840 fax, 914-887-5281

Dedoes Industries Inc. 1060 W. West Maple, P.O. Box 575 Walled Lake, MI 48390 248-624-7710 800-521-7086 fax, 248-624-5080

DeFelsko Corp. 802 Proctor Ave., P.O. Box 676 Ogdensburg, NY 13669-0676 315-393-4450 800-448-3835 fax, 315-393-8471
(*See our ad on page 577.*)

Degussa-Hüls Corp. 65 Challenger Rd. Ridgefield Park, NJ 07660 201-641-6100 fax, 201-807-3111

Delavan Mfg. Co. 811 4th St. W. Des Moines, IA 50265 515-274-1561 fax, 515-271-7200

DeLong Equipment Co. 1216 Zonolite Rd., N.E. Atlanta, GA 30306 404-607-1234 800-548-8233 fax, 404-607-1000

Delrod Sales Corp. 1307 E. Michigan, P.O. Box 2168 Kalamazoo, MI 49003-2168 616-342-0262 800-635-0077 fax, 616-342-4313

Delta D.C. Power Inc. 139 Laura Dr. Addison, IL 60101 630-628-3651 fax, 630-628-5186

Delta Foremost Chemical Corp. 3915 Air Park St. Memphis, TN 38118 901-363-4340 fax, 901-375-3600

Delta Pollution Control Inc. 30540 S.E. 84th St. Preston, WA 98050 425-222-4544 800-999-2282 fax, 425-222-4560

Deltech Engineering Inc. 344 Churchmans Rd. New Castle, DE 19720 302-328-1345 fax, 302-328-4833

Denton Vacuum Inc. 1259 N. Church St. Moorestown, NJ 08057 609-439-9100 fax, 609-439-9111

Desco Inc. 1240 Howard St. Elk Grove Village, IL 60007 847-439-2130 fax, 847-439-0029
(*See our ad on page 347.*)

Design Systems Inc. 38799 W. 12 Mile Rd., Ste. 200 Farmington Hills, MI 48331 248-489-4300 fax, 248-489-4321

Desktop Dimensions Interactive Inc. 777 Annoreno Dr. Addison, IL 60101 630-628-0777 888-333-4334 fax, 630-628-0780

Despatch Industries Inc. P.O. Box 1320 Minneapolis, MN 55440-1320 612-781-5363 fax, 612-781-5353

Detector Electronics Corp. 6901 W. 110th St. Minneapolis, MN 55438 612-941-5665 800-765-3473 fax, 612-829-8750

Detrex Corp., Equipment Div. 401 Emmett Ave. Bowling Green, KY 42101 270-782-2411 800-233-3593 fax, 270-781-3425
(*See our ad on page 155.*)

Detrex Corp., Solvents and Environmental Services Div. 24901 Northwestern Hwy. Southfield, MI 48075 248-358-5800

Deveco Corp. 424 Fairview St. Belvidere, IL 61008 815-544-9797 fax, 815-544-5188
(*See our ad on page 503.*)

Diagenex Inc. 288 Lindbergh Ave. Livermore, CA 94550 510-606-5600 fax, 510-606-5643

Digital Analysis Corp. 2533 Cherry Valley Tpk., P.O. Box 163 Marcellus, NY 13108 315-673-4935 fax, 315-673-3836

Dionex Corp. 1228 Titan Way, P.O. Box 3603 Sunnyvale, CA 94088-3603 408-737-0700 800-723-1161 fax, 408-739-4398

Dipsol of America 538 Forest St. Kearny, NJ 07032 201-991-4171 fax, 201-991-5855

Direct Safety Co. 7815 S. 46th St. Phoenix, AZ 85044-5399 602-968-7009 800-528-7405 fax, 602-438-1690

Disco Inc. P.O. Box 469 Louisville, KY 40014 502-419-4587 888-615-9266
(*See our ad on page 805.*)

Distributor Resources 3499 Villa Casa Ct. Brunswick, OH 44212 330-225-7008 fax, 330-225-3315

Divine Brothers Co. 200 Seward Ave. Utica, NY 13503 315-797-0470 800-642-7456 fax, 315-797-0058
(*See our ad on page 39.*)

Division Lead Ltd. Partnership 7742 W. 61st Pl. Summit, IL 60501 708-458-4528 800-457-5323 fax, 708-458-4642
(*See our ad on page 227.*)

Dixon Ticonderoga Co. Ridgeway Blvd. Lakehurst, NJ 08733 732-657-2255 800-334-5276 fax, 732-657-2323

Donald Sales & Mfg. Co. N96 W14313 County Line Rd. Menomonee Falls, WI 53051 414-255-7414 fax, 414-255-4040

Donaldson Co. Inc., Torit Products 1400 W. 94th St., P.O. Box 1299 Minneapolis, MN 55440-1299 612-887-3131 800-365-1331 fax, 612-887-3377

Donaldson, John G. 13372 Epping Way Tustin, CA 92680 714-730-7236

Dow Chemical Co. 2020 Dow Center Midland, MI 48674 517-636-1000 800-447-4369

Dow Corning Corp. P.O. Box 0994 Midland, MI 48686-0994 517-496-6000 800-252-9899 fax, 517-496-8026

Dreher Corp. 57 George Leven Dr. N. Attleboro, MA 02760 508-695-0303 fax, 508-699-7420
(*See our ad on page 109.*)

Dri-Dek Corp. 2706 S. Horseshoe Dr. Naples, FL 33942 941-643-1661 800-348-2398 fax, 941-643-2376

Dry Vac Environmental 101 N. Front St. Rio Vista, CA 94571 707-374-7500 800-992-9113 fax, 707-374-7505

Du-Lite Corp. 171 River Rd. Middletown, CT 06457 860-347-2505 fax, 860-347-9404
(*See our ad on page 473.*)

Duall Div., Met-Pro Corp. 1550 Industrial Dr. Owosso, MI 48867-9799 517-725-8184 fax, 517-725-8188
(*See our ad on page 783.*)

DuBois, Div. of Diversey Lever 255 E. 5th St., Ste. 1200 Cincinnati, OH 45202-4799 513-762-6000 800-438-2647 fax, 513-762-6601

Dudick Corrosion Proof Inc. 1818 S. Wason Dr. Streetsboro, OH 44241 216-562-1970 800-322-1970 fax, 216-562-7638

Duggan Masking Devices 7075 Lyndon Ave. Detroit, MI 48238 313-864-2550 800-669-8518 fax, 313-864-9210

DuPont Co. 1007 Market St., Rm. B-13303 Wilmington, DE 19898 800-441-7515 fax, 302-774-7573

DuPont Polymers, Filament Products Rte. 892 (DuPont Rd.), Bldg. 158 Washington, WV 26181 304-863-4908 800-635-9695 fax, 304-863-2779

DuPont, Fluoro Polymers Div. Chestnut Run Plaza, Rm. 1254 C, P.O. Box 80-0702 Wilmington, DE 19880 302-996-7120 800-441-9281

Duraline Abrasives Inc. 62 Mill St. Lockport, NY 14094-2460 716-438-0047 800-283-0483 fax, 716-438-9931

Duriron Co. Inc., Engineered Systems Group 9542 Hardpan Rd. Angola, NY 14006 716-549-2500 fax, 716-549-3950

Duriron Co. Inc., Valve Div. P.O. Box 2609 Cookeville, TN 38509 615-432-4021 fax, 615-432-5518

Durr Ecoclean 50055 Pontiac Trail Rd. Wixom, MI 48393 248-960-4360 fax, 248-960-4633

Dymax Corp. 51 Greenwoods Rd. Torrington, CT 06790 860-482-1010 fax, 860-496-0608

Dynabrade Inc. 8989 Sheridan Dr. Clarence, NY 14031-1490 716-631-0100 fax, 716-631-2073

Dynaloy Inc. 1910 S. State Ave., P.O. Box 33609 Indianapolis, IN 46203 317-788-5694 800-669-5709 fax, 317-788-5690

Dynamold Solvents Inc. P.O. Box 9617 Fort Worth, TX 76147-2617 817-335-0862 fax, 817-877-5203

Dynaphore Inc. 2709 Willard Rd. Richmond, VA 23294 804-288-7109 fax, 804-282-1325

Dynapower Corp. 1020 Hinesburg Rd., P.O. Box 9210 S. Burlington, VT 05407 802-860-7200 800-292-6792 fax, 802-864-3782
(See our ad on page 685.)

Dynatec Systems Inc. 909 Jacksonville Rd. Burlington, NJ 08016-3813 609-387-0330 fax, 609-387-2060

Dynatronix Inc. 462 Griffin Blvd. Amery, WI 54001 715-268-8118 800-826-7172 fax, 715-268-8183
(*See our ad on page 689.*)

Dynavac, A Tenney Co. 110 Industrial Park Rd. Hingham, MA 02043 781-740-8600 fax, 781-740-9996

Dynetics Corp. 30 Nashua St. Woburn, MA 01880 781-933-2680 fax, 781-933-9028

E

E/M Engineered Coating Solutions 100 Cooper Cir., P.O. Box 3969 Peachtree City, GA 30269-7969 770-261-4800 888-233-4706 fax, 770-261-4801
(*See our ad on page 515.*)

ECI Technology Inc. 1 Madison St. E. Rutherford, NJ 07073 973-773-8686 fax, 973-773-8797
(*See our ad on page 5.*)

EG&G Environmental 10901 Nesbitt Ave., S. Bloomington, MN 55437 612-888-5175 fax, 612-888-5321

EG&G Instruments Inc. 801 S. Illinois Ave. Oak Ridge, TN 37830 423-482-4411 fax, 423-425-1334

EM Industries Inc. 5 Skyline Dr. Hawthorne, NY 10532-2119 914-592-4660 fax, 914-592-9469

EM Science 480 S. Democrat Rd., P.O. Box 70 Gibbstown, NJ 08027 609-423-6300 fax, 609-423-4389

ESK Engineered Ceramics, Wacker Chemicals U.S.A. Inc. 535 Connecticut Ave. Norwalk, CT 06854 203-866-9400 fax, 203-866-9427

EZE Products Inc. 603 High Tech Ct., P.O. Box 5744 Greenville, SC 29650 864-879-7100 800-255-1739 fax, 864-879-7196

Eastern Smelting & Refining Corp. 37-39 Bubier St. Lynn, MA 01901 781-599-9000 800-343-0914 fax, 781-598-4880

Echo Supply 1026 Hanson Ct. Milpitas, CA 95035 408-945-0325 800-878-6924 fax, 408-945-0336

Eclipse Combustion Inc. 1665 Elmwood Rd. Rockford, IL 61103 815-877-3031 fax, 815-877-3120

Eco-Tec Inc. 1145 Squires Beach Rd. Pickering, Ont. L1W 3T9, Canada 905-427-0077 fax, 905-427-4477
(*See our ads on pages 229, 493.*)

Ecolink Inc. 1481 Rock Mountain Blvd. Stone Mountain, GA 30083 770-621-8240 800-886-8240 fax, 770-621-8245

Ecoloquip 1657 Oak Tree Dr. Houston, TX 77080 713-827-9355 888-568-5332 fax, 713-827-9396

Ecowater Industrial Systems 1270 Frontenac Rd. Naperville, IL 60563 630-961-5043 800-228-9326 fax, 630-961-5174

Edlon-PSI, Unit of Robbins & Myers P.O. Box 6010 Charleston, WV 25362 304-346-5312 fax, 304-346-7714

Edwards High Vacuum International 301 Ballardvale St. Wilmington, MA 01887 978-658-5410 800-848-9800 fax, 978-658-7969

Eidschun Engineering Inc. 5181 113th Ave., N. Clearwater, FL 33760 727-572-9867 fax, 727-573-9198
(*See our ad on page 637.*)

Eimco Process Equipment Co. 669 W. 2nd S., P.O. Box 300 Salt Lake City, UT 84110 801-526-2000 fax, 801-526-2426

Eisenmann Corp., Finishing Systems Div. 150 E. Dartmoor Dr. Crystal Lake, IL 60014 815-455-4100 fax, 815-455-1018

Elchema P.O. Box 5067 Potsdam, NY 13676 315-268-1605 800-945-3545 fax, 315-268-1709

Elcometer Inc. 1893 Rochester Industrial Dr. Rochester Hills, MI 48309-3342 248-650-0500 800-521-0635 fax, 248-650-0501

Electric Materials Co. 50 S. Washington St. North East, PA 16428 814-725-9621 800-356-2211 fax, 814-725-3620

Electro Abrasives Corp. 701 Willet Rd. Buffalo, NY 14218 716-822-2500 800-284-4748 fax, 716-822-2858
(*See our ad on page 71.*)

Electro Polish Systems Inc. N. 81 W. 12920 Leon Rd., Ste 221 Menomonee Falls, WI 53051 414-253-9780 fax, 414-251-0526
(*See our ad on page 441.*)

Electro-Glo Distribution Inc. P.O. Box 1411 La Salle, IL 61310 773-638-0120 fax, 773-224-4260

Electro-Steam Generator Corp. 1000 Bernard St. Alexandria, VA 22314 703-549-0664 800-634-8177 fax, 703-836-2581

Electrochemical Products Inc. (EPI) 17000 W. Lincoln Ave. New Berlin, WI 53151-2781 414-786-9330 fax, 414-786-9403
(*See our ad on page 473.*)

Electrochemicals 5630 Pioneer Creek Dr. Maple Plain, MN 55359 612-479-2008 800-621-0510 fax, 612-479-3344

Electrode Products Inc. 2 Milltown Rd., Union, NJ 07083 908-851-2277 800-553-5228 fax, 908-851-6906
(*See our ad on page 251.*)

Electrolyte Devices Inc. 85 Fifth Ave., Bldg. 27 Paterson, NJ 07501 973-684-6060 fax, 973-684-7744

Electromatic Equipment Co. Inc. 600 Oakland Ave. Cedarhurst, NY 11516 516-295-4300 800-645-4330 fax, 516-295-4399

Electronic Controls Design Inc. 4287-A S.E. International Way Milwaukie, OR 97222-8825 503-659-6100 800-323-4548 fax, 503-659-4422

Electronics Inc. 1520 N. Main St. Mishawaka, IN 46545 219-256-5001 800-832-5653 fax, 219-256-5222

ElektroPhysik U.S.A. Inc. 770 W. Algonquin Rd. Arlington Hts., IL 60005 847-437-6616 800-782-1506 fax, 847-437-0053

Elf Atochem North America Inc. 2000 Market St. Philadelphia, PA 19103-3222 215-419-7000 800-225-7788 fax, 215-419-7930

Eltech Systems Corp., Anode Technologies Group 100 Seventh Ave., Ste. 300 Chardon, OH 44024 440-285-0300 fax, 440-285-0302

Eltek of Rochester Inc. 1600 Clinton Ave. Rochester, NY 14621 716-342-5131 800-859-3578 fax, 716-342-4033

Emerald Sales and Consulting 846 W. Devon Dr. Gilbert, AZ 85233 800-887-6417 fax, 602-926-2036

EMI Inc. Heritage Park Rd., P.O. Box 912 Clinton, CT 06413 860-669-1199 800-243-1188 fax, 860-669-7461

Empire Abrasive Equipment Co. 2101 W. Cabot Blvd. Langhorne, PA 19047-1893 215-752-8800 fax, 215-752-9373
(*See our ad on page 97.*)

Empire Buff Co. Ltd. 1425 Tellier St. Laval, Que. H7C 2H1, Canada 514-664-1200 fax, 514-664-1427

Encycle/Texas Inc. 5500 Up River Rd. Corpus Christi, TX 78407 512-289-0035 800-443-0144 fax, 512-289-7415

Enequist Chemical Co. Inc. 100 Varick Ave. Brooklyn, NY 11237 718-497-1200 800-521-5520 fax, 718-497-2421
(*See our ad on page 445.*)

Engelhard Corp.-CLAL LP 700 Blair Rd. Carteret, NJ 07008 732-205-7451 fax, 732-205-7453

Engelhard Electro Metallics Div. 1 West Central Ave. East Newark, NJ 07029 201-268-7828 800-282-4289 fax, 201-268-7860

Engineered Systems & Designs 119A Sandy Dr. Newark, DE 19713 302-456-0446 fax, 302-456-0441

Engineering Solutions, Div. of LST Industries 7439 Hunters Land San Antonio, TX 78249 210-696-6300 888-876-9897 fax, 210-696-6301
(*See our ad on page 850.*)

Enprotec 4465 Limaburg Rd. Hebron, KY 41048-9704 606-689-4300 fax, 606-689-4322
(*See our ad on page 813.*)

Enterprise Equipment Co. Inc. 6000 Caniff Detroit, MI 48212-2537 313-366-6600 fax, 313-366-6603

Enthone-OMI Inc. 350 Frontage Rd., P.O. Box 1900 New Haven, CT 06508 203-934-8611 800-243-6089 fax, 203-932-5061
(*See our ad on the Back Cover.*)

Envirite Corp. 620 W. Germantown Pike, Ste. 250 Plymouth Meeting, PA 19462 610-828-8655 fax, 610-828-8406

Enviro Tech International Inc. 2525 W. LeMoyne Ave. Melrose Park, IL 60160 708-343-6641 fax, 708-343-4633

Enviro-Pure Inc. 2220 Plainfield Pike Cranston, RI 02921 401-464-4347 fax, 401-464-4989

Enviromet Corp. 25 Thurber Blvd., Unit 1 Smithfield, RI 02917 401-232-3360 fax, 401-943-9323

Environmental Control Systems Inc. 25 Thurber Blvd. Smithfield, RI 02917-1816 401-231-2270 fax, 401-231-2320

Environmental Plating Technology Inc. 598B Riverside Dr. Coral Springs, FL 33071 954-753-6700 800-299-6700 fax, 954-755-7744

Environmental Purification Industries 2111 Champlain St. Toledo, OH 43611 419-727-0495 fax, 419-727-0595

Environmental Services Group 452 Hudson Terr., P.O. Box 1302 Englewood Cliffs, NJ 07632 201-569-2020 800-877-2436 fax, 800-800-0389

Environmental Solvents Corp. 1840 Southside Blvd. Jacksonville, FL 32216 904-724-1990 fax, 904-724-2508

Environmental Waste Technology Inc. 1039 Chestnut St., P.O. Box 38 Newton Upper Falls, MA 02164 617-332-2877 800-445-7943 fax, 617-332-8712

Environmental Water Engineering 2335 Naomi St. Houston, TX 77054 713-796-2431 fax, 713-790-1804

EnviroPure Solutions 100 Bridge St. Wheaton, IL 60187 630-871-1001 fax, 630-871-0303

Enviroserve Inc. 1600 W. Harvard Ave. Englewood, CO 80110 303-935-6329 fax, 303-935-6825

Envirosystems Equipment Co. Inc. 4100 E. Michigan St. Tucson, AZ 85714 520-584-9001 800-999-0501 fax, 520-584-9211

EnviroSystems Inc. 5927 Waltrip Rd. Houston, TX 77087 713-644-8775 800-395-4890 fax, 713-644-8901

Epcon Industrial Systems Inc. P.O. Box 7060 The Woodlands, TX 77387 409-273-1774 800-447-7872 fax, 409-273-4600

Epoc Water Inc. 3065 N. Sunnyside Fresno, CA 93727 209-291-8144 fax, 209-291-4926

Erichsen Instruments Inc. 1350 Home Ave. Akron, OH 44310 330-633-3644 800-626-7697 fax, 330-633-1977

Eslon Thermoplastics, Div. of Sekisui America Corp. P.O. Box 240696 Charlotte, NC 28224 704-889-2431 800-578-7681 fax, 704-889-2810

Esma Inc. 450 W. Taft Dr., P.O. Box 734 South Holland, IL 60473 708-331-1855 800-276-2466 fax, 708-331-8919
(*See our ad on page 169.*)

Etus Inc. 1511 Kastner Pl. Sanford, FL 32771 407-321-7910 fax, 407-321-3098

Even Cut Abrasive Co. 850 E. 72nd St. Cleveland, OH 44103 216-881-9595 800-322-4321 fax, 216-881-9976

Exolon-ESK Co. 1000 E. Niagara St., P.O. Box 590 Tonawanda, NY 14151-0590 716-693-4550 800-962-1100 fax, 716-693-0151
(*See our ad on page 69.*)

Extech Instruments Corp. 335 Bear Hill Rd. Waltham, MA 02154 781-890-7440 fax, 781-890-7864

Extrude Hone Corp. 8075 Pennsylvania Ave. Irwin, PA 15642 412-863-5900 800-367-1109 fax, 412-863-8759

Exxon Chemical Co. P.O. Box 3272 Houston, TX 77253-3272 281-870-6000 800-526-0749 fax, 281-870-6661

F

FMT Inc. 1950 Industrial Dr. Findlay, OH 45840 419-422-0768 800-878-8011 fax, 419-422-0072

FPI Systems Inc. 50 Devine St. N. Haven, CT 06473 203-281-6161 800-883-6161 fax, 203-248-3908
(*See our ad on page 636.*)

Fab-Seal Industrial Liners Inc. 42404 Mocassin Trail Shawnee, OK 74804 405-878-0166 800-874-0166 fax, 405-878-0209
(*See our ad on page 680.*)

Fab-Tech 283 Reynolds Bridge Rd., P.O. Box 4 Thomaston, CT 06787-0004 860-283-0113 800-729-7659 fax, 860-283-6972

Fabco Plastics Wholesale Ltd. 2175A Teston Rd. Maple, Ont. L6A 1T3, Canada 905-832-0600 fax, 905-832-0992
(*See our ad on page 781.*)

Fabrication Technologies International. Ltd. P.O. Box 261 North Greece, NY 14515-0261 716-720-9823 fax, 716-225-5939

Fabrico Environmental Liners Inc. 4222 S. Pulaski Rd. Chicago, IL 60632 773-890-5350 800-621-8546 fax, 773-890-4669

Falconbridge U.S. Inc. 4955 Steubenville Pike, Ste. 245 Pittsburgh, PA 15205 412-787-0220 fax, 412-787-0287

Fanta Equipment Co. 6521 Storer Ave. Cleveland, OH 44102 216-281-1515 fax, 216-281-7755

Fantaco Inc. 755 E. 82 St. Cleveland, OH 44103 216-881-8222 fax, 216-881-5758

Faraday Technology Inc. 315 Huls Dr. Clayton, OH 45315 937-836-7749 fax, 937-836-9498

Felton Brush Inc. 315 Wilson St. Manchester, NH 03105 603-669-1970 800-258-9702 fax, 603-669-0756

Fenwal Temperature Control 400 Main St. Ashland, MA 01721 508-881-2000 fax, 508-881-6729

Ferro Corp., Powder Coatings Div. 4150 E. 56th St., P.O. Box 6550 Cleveland, OH 44105 216-641-8580 800-626-7890 fax, 216-641-8596

Fiber Bond Corp. 110 Menke Rd. Michigan City, IN 46360 219-879-4541 fax, 219-874-7502

Fil-Chem Inc., Paul Frank Div. P.O. Box 90833 Raleigh, NC 27675 919-788-0909 fax, 919-788-0908

Fil-Tech Inc. 6 Pinckney St. Boston, MA 02114 617-227-1133 800-743-1743 fax, 617-742-0686

Filter Equipment Sales Co. 99 Kinderkamack Rd. Westwood, NJ 07675 201-666-9664 fax, 201-666-3802

Filter Pump Industries, Div. of Penguin Pumps Inc. 7932 Ajay Dr. Sun Valley, CA 91352 818-504-2391 877-773-6484 fax, 818-768-7590
(*See our ads on pages 721, 741.*)

Filter Specialists Inc. 100 Anchor Rd., P.O. Box 735 Michigan City, IN 46360 219-879-3307 fax, 219-877-0632

FilterCor Inc. 7932 Ajay Dr. Sun Valley, CA 91352 818-504-9471 800-345-8375 fax, 818-768-7590
(*See our ad on page 725.*)

Filtration Group - Fluid Systems 343 W. Erie St., Ste. 320 Chicago, IL 60610 312-587-9365 fax, 312-587-9380

Filtration Products Ltd. 12257 FM 529 Houston, TX 77041-2805 713-466-4365 fax, 713-466-7523

Final Phase Inc. 23850 Pinewood Warren, MI 48091 810-754-3939 fax, 810-758-7460

Finish Thompson Inc. 921 Greengarden Rd. Erie, PA 16501-1591 814-455-4478 800-934-9384 fax, 814-455-8518

Finishers Technology Corp. 319 Main St., P.O. Box 247 East Berlin, CT 06023 860-829-1000 fax, 860-828-8716

Finishing Associates Inc. 1610 Republic Rd. Huntingdon Valley, PA 19006 215-953-1340 fax, 215-953-1342

Finishing Equipment Inc. 3640 Kennebec Dr. St. Paul, MN 55122 651-452-1860 fax, 651-452-9851
(*See our ad on page 157.*)

Finishing Systems Inc. 70 Willow Springs Cir. York, PA 17402 717-764-1106 fax, 717-764-1100

Finishing Technology 503 Brick Blvd., Ste. 106 Brick, NJ 07523 732-477-1447 fax, 732-477-1974

First Light Technology Inc. 77 Industrial Park Dr. Saco, ME 04072 207-282-4698 fax, 207-282-9884

Fischer & Porter Co. 125 E. County Line Rd. Warminster, PA 18974 215-674-6000 800-829-6001 fax, 215-674-7181

Fischer Technology Inc. 750 Marshall Phelps Rd. Windsor, CT 06095 860-683-0781 800-243-8417 fax, 860-688-8496
(*See our ad on page 569.*)

Fisher Scientific 2000 Park Ln. Pittsburgh, PA 15275-1126 412-490-8300 800-766-7000 fax, 800-926-1166

Fisher-Klosterman Inc. P.O. Box 11190 Louisville, KY 40251-0190 502-776-1505 fax, 502-774-4157

FlatPlate Inc. Cyber Center, 1600 Pennsylvania Ave. York, PA 17404 717-854-2500 fax, 717-854-0040

Flex-O-Lite Div. 101 S. Hanley Rd. St. Louis, MO 63105 314-862-2444 800-325-9525 fax, 800-541-3193

Flexi-Liner Corp. 155 N. Aspan Ave., P.O. Box 1070 Azusa, CA 91702 626-969-7702 800-423-4909 fax, 626-969-7369

Flo King Filter Systems, Custom Masters Inc. 1320 Bennett Dr. Longwood, FL 32750-6341 407-331-4634 fax, 407-331-0575

Flo-Matic Corp. 1982 Belford N. Dr. Belvidere, IL 61008 815-547-5650 800-959-1179 fax, 815-544-2287

Flow Plus Inc. 1690 Lake Drive W. Chanhassen, MN 55317 612-361-6452 800-272-9105 fax, 612-361-0972

Flow Systems Inc. 23500 64th Ave., S. Kent, WA 98032 253-872-4900 800-232-9333 fax, 253-813-3285

Flowline 3010 Old Ranch Pkwy., Ste. 250 Seal Beach, CA 90740-2750 562-598-3015 fax, 562-431-8507

Flowserve Corp. 450 N. Findlay St., P.O. Box 1145 Dayton, OH 45404 937-226-4000 fax, 937-226-4325

Fluidix Inc. 1422 Mammoth Tavern Rd., P.O. Box 1807 Mammoth Lakes, CA 93546 760-924-3768 fax, 760-924-3772

Fluidpak Inc. 7807 Redsky Dr. Cincinnati, OH 45249 513-530-0888 fax, 513-530-0893

Fluorotherm Polymers Inc. 19-F Gardner Rd. Fairfield, NJ 07004 973-575-0760 fax, 973-575-0431

Foerster Instruments Inc. 140 Industry Dr., RIDC Park W. Pittsburgh, PA 15275-1028 412-788-8976 800-635-0613 fax, 412-788-8984

Forbes Co. Inc., W.D. 129 Sixth Ave., S.E., P.O. Box 14828 Minneapolis, MN 55414 612-378-1917 fax, 612-378-1389

Foresight Technologies 1401 S. McClintock Dr. Tempe, AZ 85281 602-967-0080 fax, 602-967-0818

Formax Mfg. Corp. 3178 Bellevue Ave. Detroit, MI 48207 313-921-7030 800-242-2833 fax, 313-922-5210
(*See our ad on page 59.*)

Forward Technology Industries Inc. 13500 County Rd. 6 Minneapolis, MN 55441 612-559-1785 800-369-1489 fax, 612-559-3929

Foss NIRSystems 12101 Tech Rd. Silver Spring, MD 20904 301-680-0001 800-787-0100 fax, 301-989-1485

Freiborne Industries 15 Silverdome Industrial Park Pontiac, MI 48342 248-333-2490 fax, 248-333-2492

Fremont Industries Inc. 4400 Valley Industrial Blvd., P.O. Box 67 Shakopee, MN 55379-0067 612-445-4121 fax, 612-496-3027

Furon CHR 407 East St., P.O. Box 1911 New Haven, CT 06509-9988 203-777-3631 fax, 203-787-1725

Fusion Systems Corp. 7600 Standish Pl. Rockville, MD 20855-2798 301-251-0300 fax, 301-279-0661

Fybroc Div., Met-Pro Corp. 700 Emlen Way Telford, PA 18969 215-723-8155 fax, 215-723-2197

G

GEI International Inc. 100 Ball St., P.O. Box 6849 Syracuse, NY 13217-6849 315-463-9261 fax, 315-463-9034

GET Systems Inc. 4901-F Pan American Pl., N.E. Albuquerque, NM 87109-4370 505-342-1915 fax, 505-342-1916

GLI International Inc. 9020 W. Dean Rd. Milwaukee, WI 53224 414-355-3601 800-454-0263 fax, 414-355-8346
(*See our ad on page 129.*)

GTE Sylvania, Emissive Products Div. Portsmouth Ave. Exeter, NH 03833 603-772-4331 800-258-8290 fax, 603-772-1072

Galileo Vacuum Systems Div. 94 Rainbow Rd., P.O. Box 1158 E. Granby, CT 06026 860-653-5911 fax, 860-653-6540

Galvanotech 202 E. Highland Pkwy. Roselle, NJ 07203 908-241-3900 fax, 908-241-4268
(*See our ad on page 647.*)

Galway Pumps 11828 Old Lake Rd., P.O. Box 608 North East, PA 16428 814-725-1437 800-800-7867 fax, 814-725-5596

Gamry Instruments Inc. 734 Louis Dr. Westminster, PA 18974 215-682-9330 fax, 215-682-9331

Gardner Co. Inc., Paul N. 316 N.E. First St., P.O. Box 10688 Pompano Beach, FL 33061-6688 954-946-9454 800-762-2478 fax, 954-946-9309
(*See our ad on page 579.*)

Garfield Refining Co. 810 E. Cayuga St. Philadelphia, PA 19124 215-743-4653 800-523-0968 fax, 215-533-5902

Gehnrich Oven Sales Co. 63 Mall Dr. Commack, NY 11725 631-864-2880 fax, 631-864-2871

Geib Refining Corp. 399 Kilvert St. Warwick, RI 02886 401-738-8560 800-228-4653 fax, 401-732-2841

General Chemical Corp. 90 E. Halsey Rd. Parsippany, NJ 07054 973-515-0900 800-631-8050 fax, 973-515-3232
(*See our ad on page 309.*)

General Electric Co. 24400 Highland Rd. Richmond Heights, OH 44143 216-266-2451

General Production Devices, A Div. of Lift Industries Inc. 2322 1-70 Frontage Rd. Grand Junction, CO 81505 970-245-0408 800-742-5473 fax, 970-245-9674

General Vacuum 190A Alpha Park, P.O. Box 43659 Cleveland, OH 44143 440-646-9986 888-646-9986 fax, 440-646-9987

George Fischer Inc. 2882 Dow Ave. Tustin, CA 92780-7285 714-731-8800 800-854-4090 fax, 714-731-6201
(*See our ad on page 769.*)

George Scott International Inc. 3350 McLemore Dr. Pensacola, FL 32514-7075 850-479-4667 fax, 850-479-4964

Gerson Co., Louis M. 15 Sproat St. Middleboro, MA 02346 508-947-4000 fax, 800-443-7766

Gesswein & Co., Paul H. 255 Hancock Ave., P.O. Box 3998 Bridgeport, CT 06605-0936 203-366-5400 800-243-4466 fax, 203-366-3953

Giant Distillation & Recovery Co. 900 N. Westwood Toledo, OH 43607 419-531-4600 fax, 419-531-6836

Gilbert & Jones Inc. 34 Ronzo Rd. Bristol, CT 06010 203-585-0698 fax, 203-585-7378

Glassmaster Monofilament Div. P.O. Box 826 Lexington, SC 29072 803-359-0706 fax, 803-359-0074

Glo-Quartz Electric Heater Co. Inc. 7084 Maple St. Mentor, OH 44060 216-255-9701 fax, 314-255-7852

Global Industrial Liner Inc. 5311 Country Club Dr. Victoria, TX 77904 512-574-9131 fax, 512-574-7818

Gloerfeld Co., Hermann, Div. of Wheelabrator Allevard Ent. Co. 1 Abrasive Ave., P.O. Box 804 Bedford, VA 24523 540-586-0856 800-358-7468 fax, 540-586-6286

Goad Co. 260 Old State Rd. Ellisville, MO 63021 314-394-6334 800-733-4623 fax, 314-394-2169

Goff Corp., Div. George Fischer Foundry Systems Inc. P.O. Box 1607 Seminole, OK 74868 405-382-6900 800-654-4633 fax, 405-382-7013

Goldschmidt Industrial Chemical Corp. 941 Robinson Hwy., P.O. Box 279 McDonald, PA 15057-0279 412-796-1511 800-426-7273 fax, 412-922-6657

Goodman & Co. Inc., C. 75 Spruce St., P.O. Box 2777 Paterson, NJ 07509 973-278-1303 800-468-1303 fax, 973-278-5721

Goodnature Products Inc. P.O. Box 866 Buffalo, NY 14240 716-855-3325 fax, 716-855-3328

Gordon Brush Mfg. Co. Inc. 6247 Randolph St. Commerce, CA 90040-3514 323-724-7777 fax, 323-724-1111

Gordon Products Inc. 67 Del Mar Dr. Brookfield, CT 06804 203-775-4501 fax, 203-775-1162

Grace & Co., W.R. 6000 W. 51st St. Chicago, IL 60638 708-458-0340 800-232-6411 fax, 708-563-1735

Grav-i-Flo Corp. 400 Norwood Ave. Sturgis, MI 49091 616-651-5467 fax, 616-651-7110

Graver Technologies Inc. 200 Lake Dr. Glasgow, DE 19702-3319 302-731-1700 888-353-0303 fax, 302-731-1707
(*See our ad on page 721.*)

Graver Water Systems Inc., Div. of Graver Co. 750 Walnut Ave. Cranford, NJ 07016 908-653-4200 877-472-8379 fax, 908-653-4300

Graves Co. 1800 Andrews Ave., Ext. N Pompano Beach, FL 33069 954-960-0300 800-327-9103 fax, 954-960-0301

Graymills Corp. 3705 N. Lincoln Ave. Chicago, IL 60613-3594 773-248-6825 888-472-9645 fax, 713-477-8673
(*See our ad on page 743.*)

Great Lakes Environmental 463 Vista Addison, IL 60101 630-543-9444 fax, 630-543-1169

Great Lakes Filter 5151 S. Loraine St. Detroit, MI 48208 313-894-1950 800-521-8565 fax, 313-894-2167

Great Western Chemical 808 S.W. 15th Ave. Portland, OR 97205 503-228-2600 fax, 503-221-5752

Greco Bros. Inc. 1 Greco Ln. Providence, RI 02909-2616 401-421-9306 fax, 401-274-8910

Green Products Co. P.O. Box 756 Conrad, IA 50621 515-366-2001 800-247-7807 fax, 515-366-2366

Green Technology Group 58 N. Quaker Hill Rd. Pawling, NY 12564 914-855-0331 fax, 914-855-5806

Gretch Electronics Inc. 655 Scugo Lane 12 Uxbridge, Ont. L9P 1R3, Canada 905-852-5652 fax, 905-852-6211

Grewe Plastics 123 S. 15th St. Newark, NJ 07107 973-485-7602 800-227-0076 fax, 973-485-7650

Grieve Corp. 500 Hart Rd. Round Lake, IL 60073-2898 847-546-8225 fax, 847-546-9210

Grinding & Polishing Machinery Corp. 2801 Tobey Dr. Indianapolis, IN 46219-1481 317-898-0750 fax, 317-899-1627
(*See our ad on page 47.*)

Gusher Pumps Inc. 22 Ruthman Dr. Dry Ridge, KY 41035 606-824-5001 fax, 606-824-3011

Guyson Corp. of U.S.A. W.J. Grande Industrial Park Saratoga Springs, NY 12866-9044 518-587-7894 800-633-6677 fax, 518-587-7840

H

H&H Industrial Equipment P.O. Box 975 Union City, TN 38261 901/536-4046 fax, 901/536-4454

H.K. Equipment Inc. 235 Andover St. Wilmington, MA 01887 978-988-9466 fax, 978-988-9477

HBS Equipment Corp. 14700 Alondra Blvd. La Mirada, CA 90638-5616 714-522-4100 fax, 714-521-4488
(*See our ads on pages 627, 697.*)

HPG International Inc. Oakhill Rd., Crestwood Industrial Park Mountaintop, PA 18707 800-221-1356 fax, 800-522-4857

Hach Co. P.O. Box 389 Loveland, CO 80539 970-669-3050 800-227-4224 fax, 970-669-2932

Hammond Machinery Inc. 1600 Douglas Ave. Kalamazoo, MI 49007 616-345-7151 fax, 616-345-1710
(*See our ads on pages 41, 84.*)

Handy & Harman, Industrial Products Group 1770 Kings Hwy. Fairfield, CT 06430 203-259-8321 fax, 203-259-8264

Handy & Harman, Precious Metals Refining Div. 300 Rye St. South Windsor, CT 06074 860-289-4327 800-421-0411 fax, 860-289-6494

Hanna Instruments Inc. Highland Industrial Park, 584 Park East Dr. Woonsocket, RI 02895 401-765-7500 800-426-6287 fax, 401-765-7575

Hanovia Inc. 100 Chestnut St. Newark, NJ 07105 973-589-4300 fax, 973-589-4430

Hard Chrome Plating Consultants Ltd. 2196 W. 59th & Walworth Cleveland, OH 44102 216-631-9090 fax, 216-631-9060

Hardwood Line Mfg. Co. 4045 N. Elston Ave. Chicago, IL 60618 773-463-2600 fax, 773-463-9222
(*See our ad on page 347.*)

Harman Corp. 360 South St., P.O. Box 665 Rochester, MI 48308 248-651-4477 fax, 248-651-4495

Harmsco Industrial Filters P.O. Box 14066 N. Palm Beach, FL 33408 561-848-9628 800-327-3248 fax, 561-845-2474

Harper Surface Finishing Systems Inc. 70 Gracey Ave., P.O. Box 688 Meriden, CT 06450 203-630-0550 fax, 203-630-0346

Harrington Industrial Plastics Inc. 14480 Yorba Ave. Chino, CA 91710 909-597-8641 800-877-4472 fax, 909-597-9826

Harrison Plastic Systems Inc. P.O. Box 184 Aurora, OH 44202 330-562-9545 fax, 330-562-8905
(*See our ad on page 787.*)

Harvel Plastics Inc. P.O. Box 757 Easton, PA 18042-0757 610-252-7355 fax, 610-253-4436

Hauzer Techno Coating USA, c/o Bodycote IMT 155 River St. Andover, MA 01810 978-470-1620 800-981-2943 fax, 978-475-2951

Haviland Products Co. 421 Ann St., N.W. Grand Rapids, MI 49504 616-361-6691 800-456-1134 fax, 616-361-9772

Hawk Creek Laboratory Inc. R.D. 1, 686 Simpson Rd., P.O. Box 686 Glen Rock, PA 17327 717-235-3849 800-637-2436 fax, 717-235-0609
(*See our ad on page 521.*)

Hawken Technologies 463 Turner Dr., Unit 103 Durango, CO 81301 970-247-4655 fax, 970-247-4814

Hayward Industrial Products Inc. 900 Fairmount Ave. Elizabeth, NJ 07207 908-351-5400 fax, 908-351-7706

Heat Systems-Ultrasonics Inc. 1938 New Highway Farmingdale, NY 11735 631-694-9555 800-645-9846

Heat Transfer Technology Inc. 701 N. 7th St. Minneapolis, MN 55411 612-338-4300 fax, 612-338-4343

Heatbath Corp. P.O. Box 2978 Springfield, MA 01102-2978 413-543-3381 fax, 413-543-2378
(*See our ad on page 13.*)

Hectrio 400 First Ave. Royersford, PA 19468 610-948-0734 800-784-9533 fax, 610-948-0744
(*See our ad on page 313.*)

Heil Process Equipment, Div. of Xerxes Corp. 34250 Mills Rd. Avon, OH 44011 216-327-6051 fax, 216-327-6071

Hendor-PE Inc. 55 Concourse Way Greer, SC 29650 864-879-0888 fax, 864-879-4237

Henkel Surface Technologies 32100 Stephenson Hwy. Madison Heights, MI 48071 248-583-9300 800-953-5858 fax, 248-589-4825
(*See our ad on page 15.*)

Heraeus Amersil Inc. 3473 Satellite Blvd. Duluth, GA 30136 770-623-6000 fax, 770-418-0688

Heraeus Materials Technology Div. 301 N. Roosevelt Ave. Chandler, AZ 85226 602-961-9200 fax, 602-961-9028

Heraeus Precious Metals Management Inc. 111 Albert Ave. Newark, NJ 07105 973-817-7878 800-334-1942 fax, 973-817-9125

Heritage Environmental Services LLC 7901 W. Morris St. Indianapolis, IN 46241 317-243-0811 800-827-4374 fax, 317-243-2046

Hermes Abrasives Ltd. 524 Viking Dr. Virginia Beach, VA 23452 757-486-6623 fax, 800-243-7637

Herr Industrial Inc. P.O. Box 5249 Lancaster, PA 17601 717-569-6619 fax, 717-569-3540

Hesse & Cie., Dr. Postfach 4020 Beilefeld 1, 4800 Germany 49 521 339 09 fax, 49 521 339 0969

Hill Acme Co. 7123 Pearl Rd. Cleveland, OH 44130 216-888-9030 fax, 216-888-9035

Hill Bros. Chemical Co. 1675 N. Main St. Orange, CA 92667-3442 714-998-8800 800-821-7234 fax, 714-998-6310

Hobart Tafa Technologies Inc. 146 Pembroke Rd. Concord, NH 03301 603-224-9585 fax, 603-225-4342

Hoffland Environmental Inc. 303 Silver Spring Rd. Conroe, TX 77303 409-856-4515 fax, 409-856-4589

Hommel Co., O. 235 Hope St. Carnegie, PA 15106 412-279-0700 fax, 412-279-1213

Hones Inc., Charles A. 607 Albany Ave., P.O. Box 518 N. Amityville, NY 11701-0518 631-842-8886 fax, 631-842-9300

Hoover & Strong Inc. 10700 Trade Rd. Richmond, VA 23236 804-794-3700 fax, 804-794-5687

Hoover Container Sales & Service Inc., Subsidiary of Hoover Group Inc. 2001 Westside Pkwy., Ste. 155 Alpharetta, GA 30201 404-644-4047 fax, 404-664-2850

Hoover Precision Products 500 Jonesborough Rd. Erwin, TN 37650 423-743-9121 fax, 423-743-8050

Horner, J.D. 4120 Lake Pointe Ln. Milford, MI 48382 810-363-3548

Horsehead Resource Development Inc. 900 Delaware Ave. Palmerton, PA 18071 610-826-8737 800-253-5579 fax, 610-826-8993

Horton Materials & Engineering Inc. 1200 Old Corry Rd., P.O. Box 13525 Pensacola, FL 32591-1525 904-438-4111 fax, 904-438-4226

Hotpack Corp. 10940 Dutton Rd. Philadelphia, PA 19154 215-824-1700 800-523-3608 fax, 215-637-0519

Houghton International Inc. Madison & Van Buren Aves., P.O. Box 930 Valley Forge, PA 19482-0930 610-666-4000 fax, 610-666-1376

Houghton Metal Finishing Co. 1075 Windward Ridge, Ste. 180 Alpharetta, GA 30005 770-753-4892 800-638-8819 fax, 770-521-0836
(*See our ad on page 493.*)

Houston Fearless 76 Inc. 203 W. Artesia Blvd. Compton, CA 90220-5550 310-605-0755 800-421-5000 fax, 310-608-1556
(*See our ad on page 838.*)

Houston Unlimited Inc. Hwy. 290 E. Chappell Hill, TX 77426 409-836-7568 fax, 409-830-8637

Howard Hall International 223 E. Putnam Ave. Cos Cob, CT 06807 203-869-4504 fax, 203-869-1439

Hoyt Corp. 251 Forge Rd. Westport, MA 02790 508-636-8811 800-343-9411 fax, 508-636-2088

Hubbard-Hall Inc. 563 S. Leonard St., P.O. Box 790 Waterbury, CT 06720-0790 203-756-5521 800-648-3412 fax, 203-756-9017
(*See our ad on page 459.*)

Huber Construction Co. Inc. 5220 Texas Ave., P.O. Box 912 Houston, TX 77001 713/926-9623 fax, 713/926-6541

Hudson Industries Inc. P.O. Box 2212 Hudson, OH 44236 216-487-0668 fax, 216-487-0811

Hull Corp., Vacuum Components Div. 23 Bonair Dr. Warminster, PA 18974 215-674-4450 fax, 215-674-4505

Hunter Products Inc. 792 Partridge Dr., P.O. Box 6795 Bridgewater, NJ 08807 908-526-8440 fax, 908-526-8348

Hurri-Kleen Corp. 6000 Southern Industrial Dr. Birmingham, AL 35235 205-655-8808 fax, 205-655-5392

Hutson Inc., R.N. P.O. Box 8225 Dallas, TX 75205 214-559-3352 fax, 214-520-2803

Hyde Products Inc. 28045 Ranney Pkwy. Cleveland, OH 44145 440-871-4885 fax, 440-871-1143

Hydel Engineering Ltd. 566 Ridge Rd., P.O. Box 662 Welland, Ont. L3B 5R4, Canada 905-735-5492 fax, 905-735-5499

Hydro Dynamics Inc. 8 Redmond Dr. Rome, GA 30165 706-234-4111 fax, 706-234-0702

Hydro-Blast Inc. 1505 N.E. 106th St. Vancouver, WA 98686 360-546-5500 800-332-1590 fax, 360-574-2619

Hydromatix Inc. 10450 Pioneer Blvd., Bldg. 3 Santa Fe Springs, CA 90670 562-903-7786 800-221-5152 fax, 562-944-9264
(*See our ad on page 825.*)

Hyundai Titanium Co. Ltd. 168 B1L of Namdong Ind. Complex, Dojan-Dong Namdong-ku 405-310 Inchon, Korea 82 321 813 0114 fax, 82 321 813 9114

I

i^3 Inc. 1805 Cherry Hill Rd. Baltimore, MD 21230 410-547-0887 fax, 410-547-7847

ICI Americas Inc., General Chemicals Dept. 3411 Silverside Rd. Wilmington, DE 19897 302-887-4130 fax, 302-887-5302

IEECO Inc. 18242 N. 24th Ave. Phoenix, AZ 85023 602-942-9786 800-881-5093

IGC Polycold Systems Inc. 67 Mark Dr. San Rafael, CA 94903-2264 415-479-0577 fax, 415-499-0927

ILC Dover Inc. Harrington Rd., P.O. Box 266 Frederica, DE 19946 302-335-3911 800-631-9567 fax, 302-335-0762

IMC Americhem (International Metals & Chemicals) One Pitcairn Pl. Jenkintown, PA 19046 215-517-6000 fax, 215-517-6050

INCO Ltd. 145 King St., W., Ste. 1500 Toronto, Ont. M5H 4B7, Canada 416-361-7776 fax, 416-361-7739

IPEC 1047 E. Acacia St. Ontario, CA 91761 909-930-0999 fax, 909-930-0900

IPR Systems Inc. 11651 S. Mayfield Ave. Alsip, IL 60803 708-385-7500 fax, 708-385-7515

ITT Jabsco 1485 Dale Way Costa Mesa, CA 92626 714-545-8251 fax, 714-957-0609

ITW Gema 3939 W. 56th St., P.O. Box 88220 Indianapolis, IN 46208 317-298-5000 800-628-0601 fax, 317-298-5117

ITW Ransburg Electrostatic Systems 320 Phillips Ave., P.O. Box 913 Toledo, OH 43697-0913 419-470-2000 800-233-3366 fax, 419-470-2270

ITW Vortec 10125 Carver Rd. Cincinnati, OH 45242-9976 513-891-7474 800-441-7475 fax, 513-891-4092

Ideal Rack Inc. 26 Nelson St. E. Hartford, CT 06108 860-289-7901 fax, 860-528-9933
(*See our ad on page 709.*)

Iding Co. Inc., M.P. 3420 W. Pierce St. Milwaukee, WI 53215 414-645-7560 fax, 414-645-9392

Illinois Blower Inc. 750 Industrial Dr. Cary, IL 60013-1988 847-639-5500 fax, 847-639-9527

Impco Inc. 335 Valley St. Providence, RI 02908 401-521-2490 fax, 401-521-5690

Imperial Industries Inc. 5850 Sheldon Rd. Belleville, MI 48111 734-397-1400 800-521-3540 fax, 734-397-1403
(*See our ad on page 360.*)

Imperial Zinc Corp. 1031 E. 103rd St. Chicago, IL 60628 773-264-5900 fax, 773-264-5910

Imprex Inc. 3260 S. 108th St. Milwaukee, WI 53227 414-321-9300 fax, 414-321-9086

Indco Inc. P.O. Box 589 New Albany, IN 47150-0589 812-945-4383 800-942-4383 fax, 800-942-9742

Indesco Products Inc. 4N 352 84th Ct., P.O. Box 88087 Carol Stream, IL 60188 630-462-0933 fax, 630-462-1051

Indium Corp. of America 1676 Lincoln Ave. Utica, NY 13502 315-853-4900 800-446-3486 fax, 315-853-1000
(*See our ad on page 263.*)

Industrial Chemical & Equipment, Div. of Hawkins Chemical Inc. 3230 E. Hennepin Ave. Minneapolis, MN 55413 612-378-7581 fax, 612-378-1343

Industrial Filter & Pump Mfg. Co. 5900 Ogden Ave. Cicero, IL 60650-3888 708-656-7800 fax, 708-656-7806

Industrial Filters Co. 9 Industrial Rd. Fairfield, NJ 07006 973-575-0533 fax, 973-575-9238

Industrial Instruments Inc. 446 Winterhaven Dr. Newport News, VA 23606-2533 757-930-0856 fax, 757-930-3119

Industrial Plastics Fabricators Ltd. 1190 Midway Blvd., Unit 11 Mississauga, Ont. L5T 2C1, Canada 905-564-8702 fax, 905-564-8706

Industrial Washing Machine Corp. 70 B Broad St. Matawan, NJ 07747 732-566-4660 fax, 732-566-2201

Infinitex P.O. Box 409 Clarence Center, NY 14032 716-741-8381 fax, 716-741-9649

Inmetco 245 Portersville Rd., P.O. Box 720 Ellwood City, PA 16117 412-758-5515 fax, 412-758-9311

Innotec Group Inc. 61 W. Moreland Rd. Simi Valley, CA 93065 805-522-9040 fax, 805-522-6017

Innovac Corp. 50 Harrison St. Hoboken, NJ 07030 201-963-5450 877-877-1556 fax, 201-963-5449

Instron Corp. 100 Royall St. Canton, MA 02021-1089 781-828-2500 fax, 781-575-5750

Instruments SA Group 3880 Park Ave. Edison, NJ 08820 732-549-7144 fax, 732-549-5125

Intellect Systems & Marketing Inc. 45 Knickerbocker Ave. Bohemia, NY 11716 631-567-3330 fax, 631-567-3520

International Chemical Co. 2628 N. Mascher St. Philadelphia, PA 19133 215-739-2313 fax, 215-423-7171

International Metals and Chemicals Group One Pitcairn Pl., Ste. 1200, 165 Twp. Line Rd. Jenkintown, PA 19046-3593 215-517-6000 800-220-6800 fax, 215-517-6050

International Metals Reclamation Co. P.O. Box 720 Ellwood City, PA 16117 412-758-5515 fax, 412-758-9311

International Nickel Inc. Park 80 West, Plaza 2 Saddle Brook, NJ 07662 201-368-4808 fax, 201-368-4858

International Products Corp. P.O. Box 70 Burlington, NJ 08016-0070 609-386-8770 fax, 609-386-8438

International Specialty Products 1361 Alps Rd. Wayne, NJ 07470 973-628-4000 800-622-4423 fax, 973-628-3865

International Surface Technology Ltd. 9 Owl Close, Moulton Park Northhampton NM3 1HZ, U.K. 44 604 670327

InterNet Inc. 2730 Nevada Ave., N. Minneapolis, MN 55427 612-541-9690 800-328-8456 fax, 612-541-9692

Intrepid Industries Inc. P.O. Box 443 Whitehouse Station, NJ 08889 908-534-5300 fax, 908-534-4338
(*See our ad on page 293.*)

Ion Exchange Products Inc. 4834 S. Halsted St. Chicago, IL 60609 773-254-1300 fax, 773-847-7243

Ion Tech Inc. 2330 E. Prospect Fort Collins, CO 80525 970-221-1807 fax, 970-493-1439

Ionics Inc., Separations Technology Div. 65 Grove St. Watertown, MA 02172 617-926-2500 800-338-9238 fax, 617-926-4304

Ionsep Corp. P.O. Box 258 Rockland, DE 19732 302-798-7402 fax, 302-798-7425

Iowa Engineered Processes Corp. 2395 Jamestown Ave., S.W. Independence, IA 50644 319-334-7274 fax, 319-334-6049

Ipsen International Inc. P.O. Box 6266 Rockford, IL 61125-1266 815-332-4941 800-727-7625 fax, 815-332-4995

Isco Inc., Environmental Div. 531 Westgate Blvd. Lincoln, NE 68528-1586 402-474-2233 800-228-4373 fax, 402-458-5501

Iso-Cor Inc. P.O. Box 2020 Schiller Park, IL 60176 847-678-1470 fax, 847-678-8464

Isoflux Inc. P.O. Box 79 Rush, NY 14543 716-334-2100 fax, 716-334-2100

Ivek Corp. Fairbanks Rd. N. Springfield, VT 05150 802-886-8278 800-356-4746 fax, 802-886-8274

Iwaki Walchem Corp. 5 Boynton Rd., Hopping Brook Park Holliston, MA 01746-1446 508-429-1440 fax, 508-429-1386
(*See our ad on page 744.*)

J

J Mark Systems Inc. 701 Three Mile Rd., N.W. Grand Rapids, MI 49504 616-784-6005 fax, 616-784-5655

J-Tech LLC 10 Front St., P.O. Box 384 Collinsville, CT 06022 860-693-8090 fax, 860-693-8899

J. Brinkman Co. Ltd. 225 Lorne Ave. Chatham, Ont. N7M 6J6, Canada 519-352-0208 fax, 519-352-2558

JNJ Industries Inc. 195 E. Main St., Ste. 303 Milford, MA 01757 508-478-8757 800-554-9994 fax, 508-478-2221

JP Tech 2920 Main St. East Troy, WI 53120-0863 414-642-7671 fax, 414-642-7681

JPS Technologies Inc. 11110 Deerfield Rd. Cincinnati, OH 45242 513-984-6400 fax, 513-984-8204

JSA 10620 N. Port Washington Rd. Mequon, WI 53092 414-241-3200 fax, 414-241-8712

Jaca Corp. 550 Pinetown Rd. Ft. Washington, PA 19034 215-643-5466 fax, 215-643-2772

JacksonLea, A Unit of Jason Inc. P.O. Box 699 Conover, NC 28613 828-464-1376 800-438-6880 fax, 828-464-7094
(*See our ad on page 47.*)

Jalco Associates P.O. Box 505 Woburn, MA 01801 781-935-2753 fax, 781-391-8922
(*See our ad on page 229.*)

Jarvis Mfg. 125 Space Park, S. Nashville, TN 37211 615-781-3092 fax, 615-781-3093

Jaygo Inc. 675 Rahway Ave. Union, NJ 07083-6631 908-688-3600 fax, 908-688-6060

Jaynor Inc. P.O. Box 429 Cary, IL 60013 847-639-7738 fax, 847-639-7738
(*See our ad on page 257.*)

Jema-American Inc. P.O. Box 206 Dunellen, NJ 08812 732-968-5333 fax, 732-968-1269

Jenkins' Sons Inc., M.W. 444 Pompton Ave., P.O. Box 303 Cedar Grove, NJ 07009 973-239-5150 800-278-7437 fax, 973-239-8087

Jensen Fabricating Engineers Inc. 555 Wethersfield Rd. Berlin, CT 06037 860-828-6516 fax, 860-828-0473
(*See our ad on page 177.*)

Jescar Enterprises Inc. 200 Airport Executive Park Spring Valley, NY 10977 914-352-5850 fax, 914-425-1366

Jessup Engineering Inc. 2745 Bond St. Rochester Hills, MI 48309-3572 248-853-5600 fax, 248-853-7530
(*See our ad on page 625.*)

Jet Air Technologies 401 Miles Dr. Adrian, MI 49221 517-263-0113 fax, 517-263-0038

Jet Edge, A Div. of TC/American Monorail Inc. 825 Rhode Island Ave., S. Minneapolis, MN 55426 612-545-1477 fax, 612-545-5670

Jet Wheelblast Equipment, A Div. of B&U Corp. 401 Miles Dr. Adrian, MI 49221 517-263-0502 fax, 517-263-0038

Jiffy Mixer Co. Inc. 4120 Tigris Way Riverside, CA 92503 909-272-0838 fax, 909-279-7651

Johnson Brush Co. 58 Orne St., P.O. Box 1096 North Attleboro, MA 02760 508-695-9122 fax, 508-695-5923

Johnson Matthey Inc., Materials Technology Div. 1401 King Rd. Westchester, PA 19380 610-648-8000 fax, 610-648-8105

Johnson Systems Inc. 1480 Sequoia Dr. Aurora, IL 60506 630-907-0305 fax, 630-907-0306

Jomac Inc. 863 Easton Rd. Warrington, PA 18976-1874 215-343-0800 fax, 215-343-0912

Just Liners Inc. 35507-B Clearpond Rd Shawnee, OK 74801 405-273-4017 888-838-4017 fax, 405-878-6813

Justech Inc. 8963 Cincinnati-Columbus Rd. West Chester, OH 45069 513-755-1280 fax, 513-755-1381

Justrite Mfg. Co. 2454 Dempster St. Des Plaines, IL 60016 847-298-9250 800-798-9250 fax, 800-488-5877

K

K and M Electronics Inc. 11 Interstate Dr. W. Springfield, MA 01089-4531 413-781-1350 fax, 413-737-0608

K.C. Abrasive Co. Inc. 3140 Dodge Rd. Kansas City, KS 66115 913-342-2900 fax, 913-342-0127

KBF Pollution Management Inc. One Jasper St. Paterson, NJ 07522 973-942-7700 800-366-1426 fax, 973-942-7527

KCH Services Inc. 144 Industrial Dr., P.O. Box 1287 Forest City, NC 28043 828-245-9836 fax, 828-245-1437
(*See our ad on page 779.*)

KCH Services Inc, Engineered Services Div. 130 Liberty St., Ste. 3-B Brockton, MA 02401 508-588-6800 fax, 508-588-6868

KHI Coating 45 Enterprise Dr. Vassar, MI 48768 248-608-7069 fax, 248-608-7069

KME America Inc. 1000 Jorie Blvd., Ste. 111 Oak Brook, IL 60523 630-990-2025 fax, 630-990-0258
(*See our ad on page 14.*)

KSV Instruments P.O. Box 192 Monroe, CT 06468 203-268-1745 800-280-6216 fax, 203-459-0437

Kaeser Compressors Inc. 511 Signma Dr., P.O. Box 946 Fredericksburg, VA 22404 540-898-5500 800-777-7873 fax, 540-898-5520

Kai Science and Technology Inc. 165 Front St. Chicopee, MA 01013 413-598-0316 fax, 413-598-0532

Kalamazoo Industries P.O. Box 2558 Kalamazoo, MI 49001 616-382-2050 fax, 616-382-0790

Kameras Instruments P.O. Box 399 Garrett Park, MD 20896 301-946-3210
(*See our ad on page 529.*)

Kaspar Electroplating Corp. Highway 95N, P.O. Box 667 Shiner, TX 77984 361-594-3327 888-527-3526 fax, 361-594-3311
(*See our ad on page 808.*)

Kemac Inc. 330 S. Liberty Independence, MO 64050 816-836-9980 800-836-8868 fax, 816-836-9981

Kemkel Corp. Luther Dr., P.O. Box 7336 Cumberland, RI 02864 401-333-5300 800-695-0792 fax, 401-728-8883

Kentain Products Ltd. 55 Howard Pl. Kitchener, Ont. N2K 2Z4, Canada 519-576-0994 fax, 519-576-0919

Kentucky Water Treatment Co. Inc. P.O. Box 206 Buckner, KY 40010 502-222-4599 fax, 502-222-4599

Kemco Instruments Co. Inc. 420 Kenazo Ave. El Paso, TX 79927 915-852-3375 800-325-3875 fax, 915-852-4084

Kerrco Inc. 220 S. Burlington Ave., P.O. Box 368 Hastings, NE 68901 402-462-4166 fax, 402-461-3219

Kett 17853 Santiago Blvd., Ste. 107 Villa Park, CA 92667 714-630-5100 800-438-5388 fax, 714-630-5105
(*See our ad on page 571.*)

Keystone Electric Co. Inc. 2807 Annapolis Rd. Baltimore, MD 21230-3594 410-539-1730 fax, 410-685-9022

Keystone Filter Div., Met-Pro Corp. 2385 N. Penn Rd. Hatfield, PA 19440 215-822-1963 fax, 215-997-1839

Kim Mfg. Inc. 1407 Kansas Ave. Kansas City, MO 64127 816-241-6000 800-444-2783 fax, 816-483-2095

Kimre Inc. P.O. Box 571240 Perrine, FL 33257-1240 305-233-4249 fax, 305-233-8687

Kinetico Inc., Engineered Systems Div. 10845 Kinsman Rd., P.O. Box 127 Newbury, OH 44065 440-564-5397 800-633-5530 fax, 440-338-8694
(*See our ad on page 827.*)

King Corp., Larry 13708 250th St. Rosedale, NY 11422-2110 718-481-8741 fax, 718-481-9859

Kinney Vacuum Co. 495 Turnpike St. Canton, MA 02021 781-828-9500 fax, 781-828-5612

KiwiTech International. Pty. Ltd. 380 Woodmoor Dr. Monument, CO 80132 719-488-1060 800-392-4941 fax, 719-481-2740

Kleer-Flo Co. 15151 Technology Dr. Eden Prairie, MN 55344 612-934-2555 800-328-7942 fax, 612-934-3909

Kleiber & Schulz Inc. 2017 New Highway Farmingdale, NY 11735 631-293-6688 fax, 631-293-1856

Klever Kleen Corp. 2410 S. 179th St. New Berlin, WI 53146 414-789-1947 800-699-5587 fax, 414-789-1880

Klingspor Abrasives Inc. 2555 Tate Blvd., S.E., P.O. Box 2367 Hickory, NC 28603 828-322-3030 800-645-5555 fax, 828-322-6060

Koch Engineering Co. Inc. 4111 East 37th St., N. Wichita, KS 67220 316-832-5110 fax, 316-832-6843

Koch Membrane Systems Inc. 850 Main St. Wilmington, MA 01887-3388 978-657-4250 800-343-0499 fax, 978-657-5208

Koch Sons LLC, George 10 S. 11th Ave Evansville, IN 47744 812-465-9600 888-873-5624 fax, 812-465-9876

Kocour Co. Inc. 4800 S. St. Louis Ave. Chicago, IL 60632 773-847-1111 fax, 773-847-3399
(*See our ad on page 573.*)

Kolene Corp. 12890 Westwood Ave. Detroit, MI 48223-3472 313-273-9220 800-521-4182 fax, 313-273-5207

Komax Systems Inc. 508 East E St. Wilmington, CA 90744 310-830-4320 fax, 310-830-9826

Komline-Sanderson Engineering Corp. 12 Holland Ave. Peapack, NJ 07977-0257 908-234-1000 fax, 908-234-9487

Kontek Ecology Systems Inc. 4450 Corporate Dr., Unit 1 Burlington, Ont. L7L 5R3, Canada 905-332-8366 fax, 905-332-8367

Koslow Scientific Co. 75 Gorge Rd. Edgewater, NJ 07020 201-941-4484 800-556-7569 fax, 201-941-4485

Kraft Chemical Co. 1975 N. Hawthorne Ave. Melrose Park, IL 60160 708-345-5200 800-345-5200 fax, 708-345-4005
(*See our ad on page 214.*)

Kramer Industries Inc. 1189 Sunrise Hwy. Copiague, NY 11726 631-842-4500 800-346-0209 fax, 631-265-3524

Krautkramer Branson 50 Industrial Park Rd. Lewiston, PA 17044 717-242-0327 fax, 717-242-2606

Kurts & Wolfe Chemical Co. Inc. 960 Close Ave. Bronx, NY 10473 718-328-1500 fax, 718-893-8070

Kushner Electroplating School 732 Glencoe Ct. Sunnyvale, CA 94087 408-749-8652 fax, 408-749-0176
(*See our ad on page XX.*)

Kyzen Corp. 430 Harding Industrial Dr. Nashville, TN 37211 615-831-0888 800-845-5524 fax, 615-831-0889

L

L&R Mfg. Co. 577 Elm St., P.O. Box 607 Kearny, NJ 07032-0607 201-991-5330 800-572-5326 fax, 201-991-5870
(*See our ad on page 169.*)

L&T Technologies Inc. 194 S. Main St., P.O. Box 290 W. Bridgewater, MA 02379 508-586-9972 fax, 508-586-1630

L-Chem Inc. 13909 Larchmere Blvd. Shaker Heights, OH 44120 216-932-4248 fax, 216-932-4248

L.C. Fabricators Inc. 4 St. Marks St. Linden, NJ 07036 908-486-5151 fax, 908-486-5180

LCI Corp. P.O. Box 16348 Charlotte, NC 28297-8804 704-394-8341 fax, 704-392-8507

LMI, Div. of Milton Roy 8 Post Office Sq. Acton, MA 01720 978-263-9800 fax, 978-264-9172
(*See our ad on page 741.*)

LPS Laboratories Inc. 4647 Hugh Howell Rd., P.O. Box 105052 Tucker, GA 30084-5052 770-939-9390 800-965-4321 fax, 770-939-1627

LS Industries 710 E. 17th St. Wichita, KS 67214 316-265-7997 800-835-0218 fax, 316-265-0013

LTG Technologies Inc. 4697 W. Greenfield Ave. Milwaukee, WI 53214 414-672-7700 800-866-4434 fax, 414-672-8800

La-Man Corp. 700 Glades Ct. Portr Orange, FL 32127 904-304-0411 800-348-2463 fax, 888-905-2626

Laabs Inc. 911 N. 27th St. Milwaukee, WI 53208 800-236-0040 fax, 414-342-5222

Lab Safety Supply Inc. P.O. Box 1368 Janesville, WI 53547-1368 608-754-2345 800-356-0783 fax, 800-543-9910

Lachat Instrument 6645 W. Mill Rd. Milwaukee, WI 53218 414-358-4200 fax, 414-358-4206

Laidlaw Environmental Services Inc. 220 Outlet Pointe Blvd. Columbia, SC 29210 803-798-2993 800-845-1019 fax, 803-551-4348

Lake Buchanan Industries Inc. Route 1, P.O. Box 184-C Buchanan Dam, TX 78609 512-793-2867 888-552-5278 fax, 512-793-2869

Lake Country Mfg. Inc. P.O. Box 559 Hartland, WI 53029 414-367-8395 800-648-2833 fax, 414-367-2488

Lakewood Instruments Inc., Div. of Osmonics 4953 W. Missouri Ave. Glendale, AZ 85301-6100 602-931-7332 800-228-0839 fax, 602-931-7727

Lambertville Ceramic Mfg. Co. P.O. Box 128 Lambertville, NJ 08530 609-397-2900 fax, 609-397-2708

LaMotte Co. Route 213 N., P.O. Box 329 Chestertown, MD 21620 410-778-3100 800-344-3100 fax, 410-778-6394

Lanco Corp. 575 Byme Industrial Dr. Rockford, MI 49341 616-866-8500 fax, 616-866-8599

Landa Inc. 4275 N.W. Pacific Rim Blvd. Camas, WA 98607 360-833-9100 800-547-8672 fax, 360-833-9200

Lawrence Electronics Co. 14636 Ambaum Blvd., S.W., P.O. Box 66556 Seattle, WA 98166 206-243-7310 fax, 206-243-7588

Lazar Research Laboratories Inc. 731 N. LaBrea Ave., Ste. 5 Los Angeles, CA 90038 323-931-1433 800-824-2066 fax, 323-931-1434

Leatherwood Plastics, Div. of Leatherwood Inc. 1426 Crescent Ave. Lewisville, TX 75057 972-221-7656 fax, 972-436-5735
(*See our ad on page 619.*)

Lechler Inc. 445 Kautz Rd. St. Charles, IL 60174 630-377-6611 800-777-2926 fax, 630-377-6657

Leco Corp. 3000 Lakeview Ave. St. Joseph, MI 49085-8977 616-982-5496 fax, 616-982-8977

Leed Himmel P.O. Box 4275 Hamden, CT 06514 203-288-8484 fax, 203-248-4484

Leeds & Northrup, A Unit of General Signal 351 Sumneytown Pike, P.O. Box 3300 N. Wales, PA 19454 215-699-2000 800-533-3726 fax, 215-699-1172

Leeman Labs Inc. 6 Wentworth Dr. Hudson, NH 03051 603-886-8400 fax, 603-886-9141

Lefort, L.W. 1135 Fee Ana St. Placentia, CA 92870 714-524-3741 fax, 714-524-5486

LeKem Inc. 1600 N. Clinton Ave. Rochester, NY 14621 716-342-9360 fax, 716-342-4033

Lenser Filter Media 1000 Airport Rd., Bldg. 205 Lakewood, NJ 08701 732-370-7878 800-992-5684 fax, 732-370-8779

Lenser Filtration Inc. 1750 Oak St. Lakewood, NJ 08701 732-370-1600 fax, 732-370-8411

Lesker Co., Kurt J. 1515 Worthington Ave. Clairton, PA 15025 412-233-4200 800-245-1656 fax, 412-233-4275

Lewis Cleaning Systems LLC 102 Willenbrock Rd. Oxford, CT 06478-1033 203-264-3100 800-243-5092 fax, 203-264-3102
(*See our ad on page 162.*)

Lewis Environmental Services Inc. 550 Butler St. Etna, PA 15223 412-799-0959 fax, 412-799-0958

Leybold Systems Inc. 120 Post Rd. Enfield, CT 06082-5625 860-741-2267 fax, 860-741-0267

Leybold Vacuum Products Inc. 5700 Mellon Rd. Export, PA 15632 412-325-6506 fax, 412-733-2550

Liberty Machine Co. Inc. 125 Derry Ct. York, PA 17403 717-848-1493 800-745-8152 fax, 717-854-2584

Licon Inc. 200 E. Government St., Ste. 130 Pensacola, FL 32501 904-434-5088 fax, 904-438-2040

Linnhoff Inc. CP 315 Succ. Jean-Talon Montreal, Que. H1S 2Z3, Canada 514-255-7447 800-480-2838 fax, 514-255-6212
(*See our ad on page 357.*)

Liquid Development Co. 3748 E. 91 St. Cleveland, OH 44105 216-641-9366 800-321-9194 fax, 216-641-6416
(*See our ad on page 367.*)

Little Giant Pump Co. 3810 N. Tulsa St., P.O. Box 12010 Oklahoma City, OK 73157-2010 405-947-2511 fax, 405-947-8720

Lockheed Aeronautical Systems Co. 86 S. Cobb Dr., Dept. 67-50 Zone 0250 Marietta, GA 30063 770-494-5267 fax, 770-494-7518

Lockwood Greene Engineers Inc. P.O. Box 491 Spartanburg, SC 29304 864-578-2000 800-845-3302 fax, 864-599-0436

Logical Technology Inc. 5113 N. Executive Dr. Peoria, IL 61614 309-689-2900 fax, 309-689-2911

Lucas & Associates, D.K. 8800 S. Ocean Dr., Ste. 1301 Jensen Beach, FL 34957 561-229-8932 fax, 561-229-5336

Lucent Technologies 236 Richard Valley Rd. Staten Island, NY 10309-2620 718-317-4491 800-221-6316 fax, 718-317-4459
(*See our ad on page 305.*)

Lucifer Furnaces Inc. 2048 Bunnell Rd. Warrington, PA 18976 215-343-0411 fax, 215-343-7388

Lufran Inc. 10200 Wellman Rd. Streetsboro, OH 44241 330-655-9797 800-726-5934 fax, 330-656-3500

Luster-On Products Inc. 54 Waltham Ave., P.O. Box 90247 Springfield, MA 01139 413-739-2543 800-888-2541 fax, 413-731-5549
(*See our ad on page 499.*)

Lutz Pumps Inc. 1160 Beaver Ruin Rd. Norcross, GA 30093-4898 770-925-1222 800-843-3901 fax, 770-923-0334
(*See our ad on page 745.*)

M

M+B Plating Racks Inc. 5400 Vanden Abeele Ville St. Laurent, Que. H4S 1P9, Canada 514-335-2436 fax, 514-335-6008

MAB International Inc. 9600 Great Hills Tr. Austin, TX 78759 512-346-2251 fax, 512-346-1032

MBA Mfg. & Supply Co. 1248 Allanson Rd. Mundelein, IL 60048 847-566-2555 fax, 847-566-2561

MKS Instruments Inc. 6 Shattuck Rd. Andover, MA 01810 978-975-2350 800-227-8766 fax, 978-975-0093

MSC Liquid Filtration Corp. 10 Dusthouse Rd. Enfield, CT 06082-1547 860-749-8316 800-237-7359 fax, 860-763-3354

MST Measurement Systems Inc. 975 Deerfield Pkwy. Buffalo Grove, IL 60089 847-808-2500 800-547-2900 fax, 847-808-9976

Mabbett & Associates Inc. 5 Alfred Cir. Bedford, MA 01730-2346 781-275-6050 800-877-6050 fax, 781-275-5651
(*See our ad on page 787.*)

MacDermid Inc. 245 Freight St. Waterbury, CT 06702-9984 203-575-5700 800-325-4158 fax, 203-575-5630
(*See our ad on page 17.*)

Maclee Chemical Co. Inc. 2065 N. Southport Ave. Chicago, IL 60614 773-929-9792 fax, 773-929-1622
(*See our ad on page 313.*)

Magnatex Pumps Inc. P.O. Box 770845 Houston, TX 77215-0845 713-972-8666 fax, 713-972-8665

Magne-Gage Sales & Service Co. Inc. 629 Packer St. Avoca, PA 18641 717-457-3477 fax, 717-457-3467
(*See our ad on page 577.*)

Magnus Equipment Group 4500 Beidler Rd. Willoughby, OH 44094 216-942-8488 800-456-6423 fax, 216-942-8590

Magnuson Product Corp. 6 Chelsea Rd. Clifton, NJ 07012 973-472-9292 fax, 973-472-5686

Malsbary Cleaning Systems 9615 Inter Ocean Dr. Cincinnati, OH 45246 513-870-0200 800-837-7576 fax, 513-870-0182

Malvern Minerals Co. 220 Runyon St., P.O. Box 1238 Hot Springs, AR 71901-1238 501-623-8893 fax, 501-623-5113
(*See our on page 71.*)

Manchester Corp. 280 Ayer Rd., P.O. Box 317 Harvard, MA 01451 978-772-2900 fax, 978-772-7731

Manderscheid Equipment & Supply 323 S. Racine Chicago, IL 60607 312-563-1958 800-373-6714 fax, 312-563-1959
(*See our ad on page 45.*)

Mandich, Ned V. 2800 Bernice Rd. Lansing, MI 60436 708-895-7710 fax, 708-895-8810

Manitou Systems Inc. 12 South St. Danbury, CT 06810 203-792-8797 fax, 203-792-7097

Manz Galvano-Technik GmbH Bahnstraβe 56a Wuppertal 11, D5600, Germany 49 202 783 026

March Mfg. Co. Inc. 1819 Pickwick Ave. Glenview, IL 60025-0087 847-729-5300 fax, 847-729-7062
(*See our ad on page 745.*)

Mardon Control Systems Inc. 1043 13th Ave., P.O. Box 554 Grafton, WI 53024 414-377-8241

Markee Corp. 1849 Westbelt Dr. Columbus, OH 43228 614-771-8989 fax, 614-771-7987

Markland Specialty Engineering Ltd. 48 Shaft Rd. Rexdale, Ont. N9W 4M2, Canada 416-244-4980 fax, 416-244-2287

Mart Corp. 2450 Adie Rd. St. Louis, MO 63043 314-567-7222 800-543-6278 fax, 314-567-6551

Martin Marietta Magnesia Specialties P.O. Box 15470 Baltimore, MD 21220-0479 410-780-5500 800-648-7400 fax, 410-780-5777

Mason Corp. 1049 U.S. Rte. 41, P.O. Box 38 Schereville, IN 46375 219-865-8040 800-326-3075 fax, 219-322-3611
(*See our ad on page 313.*)

Mass Finishing Inc. 801 Rockford Ave. E. Delano, MN 55328 612-972-6057 888-260-6277 fax, 612-972-8415

Master Builders Inc., Poly Floors and Coatings Div. 23700 Chagrin Blvd. Cleveland, OH 44122 216-831-5500 fax, 216-831-6512

Master Process Systems Inc. 228 S. Clark Tempe, AZ 85281 602-829-4969 fax, 602-829-3775

Matarah Industries Inc. 480 W. Oklahoma Ave. Milwaukee, WI 53207 414-483-4301 800-222-4799 fax, 414-483-4403

Matarese Finishing Services Inc. 415 Keim Blvd. Burlington, NJ 08016 609-386-0742 fax, 609-386-8202

Matchless Metal Polish Co. 840 W. 49th Pl. Chicago, IL 60609-5196 773-924-1515 fax, 773-924-5513
(*See our ad on page 55.*)

Materials Research Corp. 542 Route 303 Orangeburg, NY 10962 914-359-4200 fax, 914-359-0215

Materials Science Inc. 6377 Nancy Ridge Dr. San Diego, CA 92121-2247 619-623-0613 fax, 619-623-0616

Materials Science International Inc. 1660 Georgesville Rd. Columbus, OH 43228-3620 614-870-0400 fax, 614-878-6000

Maxi-Blast Inc. 630 E. Bronson St. South Bend, IN 46601 219-233-1161 800-535-3874 fax, 219-234-0792

Maxtek Inc. 2908 Oregon Ct., Bldg. G-3 Torrance, CA 90503-2683 310-320-6604 fax, 310-320-6609

Mayer Associates Manufacturers' Agent 2614 Charney Rd. University Heights, OH 44118-4405 216-321-7098 fax, 216-321-8816

McGean-Rohco Inc. 2910 Harvard Ave. Cleveland, OH 44105-3010 216-441-4900 800-932-7006 fax, 216-441-1377
(*See our ad on page 7.*)

McKean Machinery Sales Inc. 921 N. 4th St. Olean, NY 14760 716-372-7733 fax, 716-372-7807

McNab Inc. 20 N. MacQuesten Pkwy. Mount Vernon, NY 10550 914-699-1616 fax, 914-699-1671

McNichols Co. 5501 Gray St., P.O. Box 30300 Tampa, FL 33630-3300 813-289-4100 800-237-3820 fax, 813-289-7884

Meco Equipment U.S.A. Inc. 445 Bryant Blvd. Rock Hill, SC 29732 803-366-8316 fax, 803-329-7382

Media Blast & Abrasives Inc. 591 W. Apollo St. Brea, CA 92821 714-257-0484 fax, 714-257-0184

Mefiag Div., Met-Pro Corp. 160 Cassell Rd., P.O. Box 144 Harleysville, PA 19438 215-721-6030 fax, 215-723-6758
(*See our ads on page 719, 725.*)

Meller Optics Inc. 120 Corliss St., P.O. Box 6001 Providence, RI 02940 401-331-3717 800-821-0180 fax, 401-331-0519

Meloon Enterprises Inc. 419 Commerce Ln., Ste. 1 Berlin, NJ 08009 609-768-5707 800-969-3331 fax, 609-753-0482

Membranes International Inc. 52 Goodviet Pl. Glen Rock, NJ 07452 201-447-3044 fax, 201-447-2132

Memco 209 E. 11th Ave., P.O. Box 145 Roselle, NJ 07203 908-241-1200 800-526-2180

Meraco Inc. P.O. Box 631 East Candon, AR 71701 501-574-0646 fax, 501-574-0641

Merion Software Associates Inc. 5 Great Valley Pkwy. Malvern, PA 19355 610-648-3871 fax, 610-648-3876

Merit Abrasive Products Inc. 201 W. Manville Compton, CA 90224 310-639-4242 800-421-1936 fax, 310-632-2194

Mesa West Inc. 1910 Betmor Ln. Anaheim, CA 92805 714-634-2526 fax, 714-634-8560
(*See our ads on pages 229, 583, 639.*)

Met Wool Inc. 2360 E. Grand Ave. Hot Springs, AK 71901 501-624-0320 fax, 501-624-0186

Met-Chem Inc. 777 E. 82nd St. Cleveland, OH 44103 216-881-7900 fax, 216-881-8950
(*See our ad on page 803.*)

Met-Pro Corp., Systems. Div. 160 Cassell Rd., P.O. Box 144 Harleysville, PA 19438 215-723-6751 fax, 215-723-6758

Metabo Corp. 1231 Wilson Dr., P.O. Box 2287 West Chester, PA 19380 610-436-5900 800-638-2264 fax, 800-638-2261
(*See our ad on page 45.*)

Metal Chem Inc. 509 Huntington Rd. Greenville, S.C. 29615 864-288-7973 fax, 864-288-2927
(*See our ad on page 435.*)

Metal Coating Process Corp. 6101 Idlewild Rd., Ste. 134 Charlotte, NC 28212 704-563-0070 800-548-9889 fax, 704-535-4535
(*See our ad on page 445.*)

Metal Coatings International Inc. 275 Industrial Pkwy., P.O. Box 127 Chardon, OH 44024-1083 216-946-2064 fax, 216-285-5009

Metal Samples Co. Inc. 152 Metal Samples Rd., P.O. Box 8 Munford, AL 36268 256-358-4202 fax, 256-358-4515

METALAST International Inc. 2241 Park Pl. Minden, NV 89423 775-782-8324 888-638-2527 fax, 775-782-2498
(*See our ad on page 485.*)

Metalline Corp. 10620 N. Port Washington Rd. Mequon, WI 53092 414-241-3200 fax, 414-241-8712
(*See our ad on page 193.*)

Metallurgical Products Co. P.O. Box 598 West Chester, PA 19381-0598 610-696-6770 800-659-4672 fax, 610-430-8431

Metalor USA Refining Corp. 255 John L. Dietsch Blvd., P.O. Box 255 N. Attleboro, MA 02761-0255 508-699-8800 800-829-9999 fax, 508-695-1603

Metalx Inc. 2600 Roby Martin Rd. Lenoir, NC 28645 828-758-4997 fax, 828-758-5033
(*See our ad on page 453.*)

Metco Div., Perkin-Elmer 1101 Prospect Ave. Westbury, NY 11590 516-334-1300 fax, 516-338-2477

METFAB Technologies Inc. 40 Minnesota Ave. Warwick, RI 02888 401-732-6677 fax, 401-732-4466

Metorex Inc. Princeton Crossroads Corporate Ctr., P.O. Box 3540 Princeton, NJ 08543-3540 609-406-9000 800-229-9209 fax, 609-530-9055

Metre-General Inc. 9085 Marshall Ct. Westminster, CO 80030 303-430-0095 fax, 303-430-7337

Metric Systems Corp. 645 Anchors St. Ft. Walton Beach, FL 32548 904-302-3852 fax, 904-302-3856

Metz Metallurgical Corp. 3900 S. Clinton Ave. S. Plainfield, NJ 07080 908-561-1100 fax, 908-769-9456

Mibus Inc. 1635 Janet St. Downers Grove, IL 60515 630-852-8038 fax, 630-852-8054
(*See our ad on page 237.*)

MichDan Environmental Technologies Inc. 24 Carriage Way North Providence, RI 02904 401-353-7806 fax, 401-353-5699

Micro Photonics Inc. 4949 Liberty Ln., Ste. 170 Allentown, PA 18106-0129 610-366-7103 fax, 610-366-7105

Micro-Metrics Co. P.O. Box 13804 Atlanta, GA 30324 404-325-3243 fax, 404-320-1668

Micro-Set 8653 Richmond Hwy. Alexandria, VA 22309 703-360-5789 fax, 703-360-1999

Micro-Surface Finishing Products Inc. 1217 W. 3rd St., P.O. Box 818 Wilton, IA 52778 319-732-3240 800-225-3006 fax, 319-732-3390

Mid-America Industrial Liners Inc. P.O. Box 3639 Shawnee, OK 74802 405-964-5950 800-255-8618 fax, 405-964-5955

Mid-America Plastics 700 Industrial Cir., S. Shakopee, MN 55379 612-445-7667 fax, 612-445-2974

Mid-State Chemical & Supply Corp. 2100 Greenbrier Ln., P.O. Box 18227 Indianapolis, IN 46218 317-925-1407 800-486-1407 fax, 317-924-8553

Mid-Western Processes Inc. 32043 Howard St., P.O. Box 71567 Madison Heights, MI 48071 248-588-6500 fax, 248-585-8636
(*See our ad on page 634.*)

Midbrook Inc. 2080 Brooklyn Rd., P.O. Box 867 Jackson, MI 49204 517-787-3481 fax, 517-787-2349
(*See our ad on page 129.*)

Midwest Air Products Co. Inc. 281 Hughes Dr., P.O. Box 5319 Traverse City, MI 49685-5319 616-941-5865 800-976-2726 fax, 616-941-1636

Midwest Tungsten Service Inc. 7101 S. Adams St., Ste. 6 Willowbrook, IL 60521 630-325-1001 800-626-0226 fax, 630-325-3571

Mikro Industrial Finishing 170 W. Main St. Vernon, CT 06066 800-886-4576

Mikrofinish Inc. 3 Mars Ct. Boonton, NJ 07005 973-263-5551 fax, 973-263-0080

Milbank Systems Inc. 1925 Bedford Ave., P.O. Box 7509 N. Kansas City, MO 64116-0209 816-472-4674 fax, 816-472-5674

Miles Inc. 5601 Eastern Ave. Baltimore, MD 21224 410-633-9550 fax, 410-631-4395

Mill Lane Engineering Co. Inc. Middlesex Canal Technology Ctr., 70 Olde Canal Dr. Lowell, MA 01851-5298 978-937-3800 fax, 978-937-9915

Miller Thermal Inc. 555 Communication Dr. Appleton, WI 54912 920-731-6884 fax, 920-734-2160

Millhorn Chemical & Supply Co. Inc. 6142 Walker, P.O. Box 460 Maywood, CA 92070 323-771-8301 fax, 323-771-0529

Milwaukee Brush Mfg. Co. W142 N9251 Fountain Blvd., P.O. Box 830 Menomonee Falls, WI 53052-0830 414-255-3200 800-336-3444 fax, 414-255-1412

Mine Safety Appliances Co. P.O. Box 426 Pittsburgh, PA 15230 412-967-3228 800-672-2222 fax, 412-776-3280

Miraclean Cleaning Systems, Div. of Chautagqua Chemicals Co. Inc. 4743 Cramer Dr., P.O. Box 100 Ashville, NY 14710 716-763-4343 fax, 716-763-3555

Misonix Inc. 1938 New Highway Farmingdale, NY 11735 631-694-9555 800-645-9846 fax, 631-694-9412

Missouri Electrochem Inc. 10958 Lin-Valle Dr. St. Louis, MO 63123 314-894-9300 800-325-9651 fax, 314-894-9356

Mitchell Co. Inc., E.C. 88-90 Boston St., P.O. Box 607 Middleton, MA 01949-0907 978-774-1191 fax, 978-774-2494

Mitchell-Bate Co. 137 Brookside Rd., P.O. Box 1707 Waterbury, CT 06721-1707 203-754-5181 fax, 203-757-4757

Mobile Process Technology 2070 Airways Blvd., P.O. Box 14867 Memphis, TN 38114 901-744-1142 800-238-3028 fax, 901-743-2361
(*See our ad on page 850.*)

Mocap Inc. 13100 Manchester Rd. St. Louis, MO 63131 314-543-4000 800-633-6775 fax, 314-543-4111

Modern Chemical Inc. P.O. Box 368 Jacksonville, AR 72076 501-988-1311 fax, 501-988-2229

Moldsaver Inc. 345 W. 75th Pl. Miami, FL 33014 305-556-8810 800-327-2742 fax, 305-558-9255

Molectrics Inc. 4008 E. 89 St. Cleveland, OH 44105 216-641-0090 fax, 216-641-1337
(*See our ad on page 445.*)

Monitor Consultants LLC 11112 Edgebrook Ln. Indian Head Park, IL 60525 708-784-0540 fax, 708-246-6934

Monitrol Inc. 701 S. 13th St. Vincennes, IN 47591 812-886-6500 fax, 812-886-6553

Monroe Environmental Corp. 11 Port Ave., P.O. Box 806 Monroe, MI 48161 734-242-7654 800-992-7707 fax, 734-242-5275

Moon Fabricating Corp. 700 W. Morgan St., P.O. Box 567 Kokomo, IN 46903-0567 765-459-4194 fax, 765-452-6090
(*See our ad on page 19.*)

Morrison Molded Fiber Glass Co. 400 Commonwealth Ave., P.O. Box 580 Bristol, CT 24203-0580 860-669-1181 fax, 860-669-1150

Morse Mfg. Co. Inc. 727 W. Manlius St., P.O. Box 518 E. Syracuse, NY 13057 315-437-8475 fax, 315-437-1029

Morton Electronic Materials, Morton International Inc. 2631 Michelle Dr. Tustin, CA 92680 714-730-4504 fax, 714-730-4240

Morton International Inc., Ventron Div. 150 Andover St. Danvers, MA 01923 978-774-3100 fax, 978-750-9517

Mosher Co. Inc. 15 Exchange St. Chicopee, MA 01014 413-594-9605 fax, 413-594-7647

Motor Guard Corp. 580 Carnegie St. Manteca, CA 95336 209-239-9191 800-227-2822 fax, 209-239-5114

Mueller Co., Paul 1600 W. Phelps, P.O. Box 828 Springfield, MO 65801-0828 417-831-3000 800-683-5537 fax, 417-831-6642
(*See our ad on page 765.*)

Multi-Arc Inc. 200 Roundhill Dr. Rockaway, NJ 07866 973-625-3400 fax, 973-625-2244

Munson Machinery Co. Inc. 210 Seward Ave., P.O. Box 855 Utica, NY 13503-0855 315-797-0090 800-944-6644 fax, 315-797-5582
(*See our ad on page 45.*)

Myron L Co. 6115 Corte del Cedro Carlsbad, CA 92009-1516 760-438-2021 800-869-7668 fax, 760-931-9189
(*See our ad on page 141.*)

N

NCA Systems Inc. 2180 Calumet St. Clearwater, FL 34625 727-441-1661 fax, 727-441-2916

Nalco Chemical Co. One Nalco Center Naperville, IL 60563-1198 630-305-1000 fax, 630-305-2900

Nalge Co. 74 Panorama Creek Dr., P.O. Box 20365 Rochester, NY 14602-0365 716-586-8800 fax, 716-586-3294

Nano-Master Inc. 3019 Alvin Devane Blvd., Ste. 220 Austin, TX 78741 512-385-4522 fax, 512-385-4900

Napco Inc. 16 N. Harwinton Ave. Terryville, CT 06786 860-589-7800 fax, 860-589-7304
(*See our ad on page 624.*)

National Combustion Co. Inc. 59-12 54th St. Maspeth, NY 11378 718-628-1100 fax, 718-628-1159

National Exposure Testing 3315 Centennial Rd., Unit 2 Sylvania, OH 43560 419-841-1065 fax, 419-841-8716

National Rack Co. 179 Madison St. Paterson, NJ 07501 973-684-0827 fax, 973-684-1624

Nationwide Installation Corp. 950 Boston, S.E. Grand Rapids, MI 49507-2050 616-243-0050 fax, 616-243-1151

Natural Coating Systems LLC 970 Conservation Club Rd. Martinsville, IN 46151 812-597-1132 fax, 812-597-0312

Navy Brand Mfg. Co. 5111 Southwest Ave. St. Louis, MO 63110-3496 314-865-5500 800-325-3312 fax, 314-865-5509

Neeltran Inc. 71 Pickett District Rd., P.O. Box 1659 New Milford, CT 06776 860-350-5964 fax, 860-350-5024

Neptune Chemical Pump Co. P.O. Box 247 Lansdale, PA 19446 215-699-8701 fax, 800-255-4017

Netzsch Inc. 119 Pickering Way Exton, PA 19341-1393 610-363-8010 fax, 610-363-0971

New Age Chemical Inc. 1345 Pearl St. Waukesha, WI 53186 414-548-8040 800-236-8040 fax, 414-548-8049

New England Oven and Furnace Co. 385 Boston Post Rd. Orange, CT 06477 203-799-2005 fax, 203-799-8997

New England Plastic Coated Products Inc. 350 Old Colony Rd. Norton, MA 02766 508-222-3019 fax, 508-222-3049

New England Rack Co. Inc. 22A Acorn Rd. Branford, CT 06405 203-481-0303 800-767-7225 fax, 203-483-5384
(*See our ad on page 709.*)

New Holland North America Inc. 100 Brubaker Ave., P.O. Box 262 New Holland, PA 17557 717-355-1458 fax, 717-355-3440
(*See our ad on page 351.*)

New Materials Corp. 8960 Springbrook Dr., Ste. 105 Coon Rapids, MN 55433 612-786-8677 fax, 612-786-8518

New Pig Corp. One Pork Ave. Tipton, PA 16684-0304 814-684-0101 800-328-2464 fax, 814-684-4134

New Products Inc. P.O. Box 405 Meadville, PA 16335 814-336-2174 fax, 814-337-1315

New Surface Technologies 28 Industry Dr. Bedford, OH 44146 440-439-5790 fax, 440-439-5794

New York Plating Technologies Inc. 54 West Main St. Brocton, NY 14716 716-792-9363 fax, 716-792-9363

Newact Inc. 3470 Cardiff Ave. Cincinnati, OH 45209 513-321-5177 800-914-8392 fax, 513-321-5246
(*See our ad on page 347.*)

NewAge Industries Inc., Testing Instruments Group 2300 Maryland Rd. Willow Grove, PA 19090-1799 215-657-6040 fax, 215-657-1697

Newcastle Industrial Contracting 34668 Nova Mt. Clemens, MI 48043 810-791-7400 fax, 810-791-4045

Newchem Co. P.O. Box 1008 N. Attleboro, MA 02761 508-643-9313 fax, 508-643-1449

Niacet Corp. 400 47th St., P.O. Box 258 Niagara Falls, NY 14304 716-285-1474 800-828-1207 fax, 716-285-1497
(*See our ad on page 193.*)

Niagara Environmental Associates 88 Okell St. Buffalo, NY 14221 716-822-3921 fax, 716-822-0406

Nibco Inc. 1516 Middlebury St. Elkhart, IN 46516 219-295-3000 800-234-0227 fax, 219-295-3307

Nielsen & Sons Inc., John R. 260 Chapel Rd., S. South Windsor, CT 06074 860-528-2107 fax, 860-289-9393

Nikon Inc. 1300 Walt Whitman Melville, NY 11747 631-547-4200 fax, 631-547-0307

Nobles Mfg. Inc. 1105 E. Pine St. St. Croix Falls, WI 54024-0749 715/483-1884 fax, 715/483-3079

Nordic Synthesis Inc., A Cambrex Co. 2 Gillon St., Ste. A Charleston, SC 29401 843-720-8822 fax, 843-937-8002

Nordiko U.S.A. Inc. P.O. Box 8270 Webster, NY 14580-2106 716-671-3570 fax, 716-671-3579

Nordson Corp. 555 Jackson St. Amherst, OH 44001 440-988-9411 800-955-9563 fax, 440-985-1536

Norris Environmental Services 5215 S. Boyle Ave. Los Angeles, CA 90058 323-588-7111 fax, 323-588-0094

North American Mfg. Co. 4455 E. 71st St. Cleveland, OH 44105 216-271-6000 fax, 216-641-7852

North American Rectifier Ltd. 1236 Birchmount Rd. Scarborough, Ont. M1P 2C8, Canada 416-757-8339 888-289-7082 fax, 416-757-6559
(*See our ad on page 693.*)

North Coast Environmental Inc. 3200 W. 65th Cleveland, OH 44102 216-651-1710 fax, 216-651-1709

Northeastern Sonics 130 Lenox Ave., Unit 23 Stamford, CT 06906 203-348-8088 800-243-2452 fax, 203-961-1823

Norton Co. One New Bond St., P.O. Box 15008 Worcester, MA 01615-0008 508-795-5000 800-446-1119 fax, 508-795-2171

Norton Performance Plastics Corp. 150 Dey Rd. Wayne, NJ 07470-4699 973-696-4700 800-526-7844 fax, 973-696-4056

Nova Finishing Systems Inc. 1610 Republic Rd. Huntingdon Valley, PA 19006 215-942-4474 800-444-4159 fax, 215-953-1342

Nu-Matic Grinders Inc. 19870 St. Clair Ave. Euclid, OH 44117 216-531-9135 fax, 216-531-6345

Nutro Machinery Corp. 11515 Alameda Dr. Strongsville, OH 44136-3099 440-572-3800 fax, 440-572-5584

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O·I·Analytical 151 Graham Rd., P.O. Box 9010 College Station, TX 77842-9010 409-690-1711 800-653-1711 fax, 409-690-0440
(*See our ad on page 525.*)

OMG Fidelity 470 Frelinghuysen Ave. Newark, NJ 07114 973-242-4110 800-752-8336 fax, 973-242-5796

Oakite Products Inc., A Member of the Chemetall Group 50 Valley Rd. Berkeley Heights, NJ 07922-2798 908-464-6900 800-526-4473 fax, 908-464-4658
(*See our ad on page 2.*)

Oaks Industries Inc. 5700 County Rd. 3810 West Plains, MO 65775 417-277-5564 fax, 417-277-5424

Oberlin Filter Co. 404 Pilot Ct. Waukesha, WI 53188 414-547-4900 877-623-7546 fax, 414-547-0683

Occidental Chemical Corp. 5005 LBJ Frwy. Dallas, TX 75244-6119 972-404-3573 fax, 972-404-4157
(*See our ad on page 427.*)

Oil Skimmers Inc. P.O. Box 33092 Cleveland, OH 44133 440-237-4600 fax, 440-582-2759

Okuno Chemical Industries Co. Ltd. 7-10, Dosho-machi, 4-chome Chuo-ku Osaka 541 Japan 81 6 203 6667 fax, 81 6 203 0714

Olds Filtration Engineering Inc. P.O. Drawer 970 Daphne, AL 36526-0970 334-626-9492 800-841-2633 fax, 334-626-7988

Olean Finishing Machine Co. Inc. P.O. Box 522 Olean, NY 14760 716-372-5272 fax, 716-372-5315

Oliver Sales Co. 13445 Floyd Cir. Dallas, TX 752-1595 972-231-1522 fax, 972-644-3585
(*See our ad on pager 332.*)

Omega Thermo Products 205 Sunset Ave., P.O. Box 141 Stratford, WI 54484 715-687-8102 fax, 715-687-8053

Optical Dimensions 1627 W. Main St., #308 Boseman, MT 59715 406-585-2838 fax, 406-586-0135

Orpac Inc. P.O. Box 5436 Oak Ridge, TN 37831 615-482-4635 fax, 615-482-1281

Osborn International, A Unit of Jason 5401 Hamilton Ave. Cleveland, OH 44114-3997 216-361-1900 800-628-1200 fax, 216-361-1913

Osmonics Desal 760 Shadowridge Dr. Vista, CA 92083-7986 760-598-3334 fax, 760-598-3335

Osmonics Inc. 5951 Clearwater Dr. Minnetonka, MN 55343-8995 612-933-2277 800-848-1750 fax, 612-933-0141

Osmonics/Autotrol 5730 N. Glen Park Rd. Milwaukee, WI 53209-4454 414-238-4400 fax, 414-238-4402

Otec Precision Finish Inc. 132 Great Rd., Ste. 200 Stow, MA 01775 978-897-9847 fax, 978-897-5442

Oven Industries Inc. 207 Hempt Rd., P.O. Box 290 Mechanicsburg, PA 17055-0290 717-766-0721 fax, 717-766-4786

Oven Systems Inc. 4697 W. Greenfield Ave. Milwaukee, WI 53214 414-672-7700 fax, 414-672-8800

Oxyphen Products Co. P.O. Box 7 Oakville, CT 06779 203-264-4952

P

P.G. Industries Inc. 6400 Industrial Hwy. Gary, IN 46406 219-977-8493 800-872-9267 fax, 291-977-8887

PAL Sales Inc. 145 Flanders Rd. Bethlehem, CT 06751 203-266-7616 800-225-0666 fax, 203-266-7614

PCI of America 7307 MacArthur Blvd., Ste. 215 Bethesda, MD 20816 301-320-9100 fax, 301-320-5632

PCT Technology Inc. 30 Downhill Ln. Wantagh, NY 11793 516-221-4537 fax, 516-221-4537

PDI Inc. 4500 E. Speedway Blvd., #50 Tucson, AZ 85712 520-881-2556 800-238-2307 fax, 520-881-2862

PKG Equipment Inc. 367 Paul Rd. Rochester, NY 14624 716-436-4650 fax, 716-436-3751
(*See our ad on page 633.*)

PPB Inc. 236 Stanford S/C #236 Palo Alto, CA 04304 650-851-4387 fax, 650-851-4388

PPG Industries Inc. One PPG Pl. Pittsburgh, PA 15272 412-434-3131 800-243-6774 fax, 412-434-2125

PPG Pretreatment & Specialty Products 23000 St. Clair Ave. Cleveland, OH 44117 216-486-5300 800-627-6422 fax, 216-486-1214

PWR Inc. 15305 Stony Creek Way Noblesville, IN 46060 317-773-7774 800-466-7306 fax, 317-773-7779

Paasche Airbrush Co. 7440 W. Lawrence Ave. Harwood Heights, IL 60656 708-867-9191 800-621-1907 fax, 708-867-9198

Pacific Press 2418 Cypress Way Fullerton, CA 92831 714-525-0630 fax, 714-525-2664

Pall Corp., Industrial Process Group 2200 Northern Blvd. East Hills, NY 11548 516-484-5600 888/873-7255 fax, 516-621-3976

Palm Commodities International Inc. 1289 Bridgestone Pkwy. La Vergne, TN 37086 615-793-1990 fax, 615-793-1995

PanAbrasive Inc. 650 Rusholme Rd., P.O. Box 634 Welland, Ont. L3B 5R4, Canada 905-735-4691 800-207-4691 fax, 905-735-4511

Pangborn Corp. 580 Pangborn Blvd. Hagerstown, MD 21740 301-739-3500 800-638-3000 fax, 301-739-2279

Parish O Co. 2000 Washington Ave. St. Louis, MO 63103 314-241-3387 fax, 314-241-2443

Parker Systems, Div. of D.J. Parker Co. 2821 E. Philadelphia Ave., Unit D Ontario, CA 91761 909-930-2736 800-870-8777 fax, 909-930-2742

Parkson Corp. 2727 N.W. 62nd St., P.O. Box 408399 Fort Lauderdale, FL 33340-8399 954-974-6610 fax, 954-974-6182

Partlow Corp. Two Campion Rd. New Hartford, NY 13413 315-797-2222 800-866-6659 fax, 315-793-1864

Pasco 810 Tanglegate Pl. Millersville, PA 17551 717-871-1091 fax, 717-871-1092

Patclin Chemical Co. Inc. 66 Alexander St. Yonkers, NY 10701-2714 914-476-7000 fax, 914-476-0934
(*See our ad on page 451.*)

Patent Plastics Inc. 638 Maryville Pike, S.W. P.O. Box 9246 Knoxville, TN 37920 423-573-5411 800-340-7523 fax, 423-693-6007

Paterson Rubber Co. P.O. Box 8058 Haledon, NJ 07538 973-595-6661 fax, 973-595-5126

Patrick & Co. Inc., C.H. P.O. Box 2526 Greenville, SC 29602 864-244-4831 800-247-2586 fax, 864-292-0652

Patrick Co., P.N. 155 Clifford St. Providence, RI 02903 401-861-4773 fax, 401-861-9236

Pauli Systems 1820 Walters Ct., P.O. Box 2589 Fairfield, CA 94533 707-429-2434 fax, 707-429-2424

Pavco Inc. 4450 Cranwood Pkwy. Warrensville Hts., OH 44128-4004 216-332-1000 800-321-7735 fax, 216-332-1010
(*See our ad on page 326.*)

Pax Surface Chemicals Inc. 235A Robbins Ln., Bldg. 110 Syosset, NY 11791-6005 516-822-7860 fax, 516-932-9373

Peacock Laboratories Inc. 54th St. and Paschall Ave. Philadelphia, PA 19143 215-729-4400 fax, 215-729-1380

Pease & Curren Inc. 75 Pennsylvania Ave. Warwick, RI 02888 401-739-6350 800-343-0906 fax, 401-738-6449

Peerless Metal Powders & Abrasive 124 S. Military Detroit, MI 48209 313-841-5400 800-959-0320 fax, 313-841-0240

Pegco Process Laboratories Inc. Kearsarge St., P.O. Box 248 Bartlett, NH 03812-0248 603-374-2341 fax, 603-374-2366

Pellu Systems Inc. 1040 Northside Dr. Atlanta, GA 30318 404-876-6778 fax, 404-876-6780
(*See our ad on page 807.*)

Penetone Corp. 74 Hudson Ave. Tenafly, NJ 07670 201-567-3000 800-631-1652 fax, 201-569-5340

Penfield Liquid Treatment Systems 8 West St. Plantsville, CT 06479-1141 860-621-9141 800-522-9141 fax, 860-621-2380

Perkin-Elmer Corp. 761 Main Ave. Norwalk, CT 06859-0310 203-762-1000 fax, 203-762-6000

Permacel P.O. Box 671 New Brunswick, NJ 08903 732-418-2400 800-367-8273 fax, 732-418-2739

Petroferm Inc. 5415 First Coast Hwy. Fernandina Beach, FL 32034 904-261-8286 800-881-8816 fax, 904-261-6994

Pfeiffer Vacuum Inc. 24 Trafalgar Sq. Nashua, NH 03063-1988 603-578-6500 800-248-8254 fax, 603-578-6550

Pferd Inc. 30 Jytek Dr. Leominster, MA 01453 978-840-6420 fax, 978-840-6421

Phibro-Tech Inc. 1 Parker Plaza Fort Lee, NJ 07024 201-944-6000 fax, 201-944-7916
(*See our ad on page 239.*)

Phibro-Tech Inc., Environmental Recovery Services Div. 1 Parker Plaza Ft. Lee, NJ 07024 201-944-6020 800-777-1850 fax, 201-944-7916
(*See our ad on page 235.*)

Phifer Wire Products Inc. P.O. Box 1700 Tuscaloosa, AL 35403 205-345-2120 800-633-5955 fax, 205-759-4450

Philip Machine Co. 184 Woonasquatucket Ave. N. Providence, RI 401-353-7383 fax, 401-353-8430
(*See our ad on page 707.*)

Philipp Brothers Chemicals Inc. 1 Parker Plaza Fort Lee, NJ 07024 201-944-6020 fax, 201-944-7916

Phoenix Electrode Co. 6103 Glenmont Houston, TX 77081 713-772-6666 800-522-7920 fax, 713-772-4671

Phoenix Process Technologies Inc. 486 Norristown Rd., Ste. 231 Blue Bell, PA 19422 800-315-6369 fax, 610-238-0705

Photo Emission Technology Inc. 766 Lakefield Rd., Ste. H Westlake Village, CA 91361 805-379-9759 fax, 805-379-4362

Pick Heaters Inc. P.O. Box 516 West Bend, WI 53095 414-338-1191 800-233-9030 fax, 414-338-8489

Pilot Chemical Co. 11756 Burke St. Santa Fe Springs, CA 90670 562-698-6778 800-707-4568 fax, 562-945-1877

Pinnacle Technologies Inc. 681 Lawlins Rd., Bay 140 Wyckoff, NJ 07481 201-891-2479 fax, 201-891-7930

Plasfab Inc. 21 Quinton St. Warwick, RI 02888 401-461-1810 fax, 401-461-4147
(*See our ad on page 635.*)

Plasmag Pump Co., Div. of Murdock Co. 936 Turret Ct. Mundelein, IL 60060 847-566-0050 800-345-1956 fax, 847-566-0057

Plasmatron Coating Systems Inc. 102 Executive Dr., Unit 4-5 Moorestown, NJ 08057 609-439-0991 fax, 609-439-9288

Plast-O-Matic Valves Inc. 1384 Pompton Ave. Cedar Grove, NJ 07009-1095 973-256-3000 fax, 973-256-4745
(*See our ad on page 744.*)

Plastech Inc. P.O. Box 732 Deer Park, NY 11729 631-586-2360 fax, 631-586-2209

Plastic Methods Co. 20 W. 37th St., 7th Fl. New York, NY 10018 212-695-0070 fax, 212-967-5015
(*See our ad on page 351.*)

Plastinetics Inc. 439 Main Rd., Rte. 202, P.O. Box 322 Towaco, NJ 07082 973-316-6600 800-627-7473 fax, 973-316-0300

Platers Technical Service Inc. 1319 W. North Ave. Chicago, IL 60622 773-772-4830 fax, 773-772-5870

Plating Engineering and Chemicals Co. Ltd. PENC Bldg., 16 Dai Fu St., Tai Po Industrial Estate Tai Po, N.T. Hong Kong 852 2664 4044 fax, 852 2664 3308

Plating Process Systems Inc. 7561 Tyler Blvd., Ste. 5 Mentor, OH 44060 216-951-9667 fax, 216-951-9077

Plating Products Co. Inc. 840 Colfax Ave., P.O. Box 368 Kenilworth, NJ 07033 908-241-5040 fax, 908-241-5356
(*See our ad on page 641.*)

Plating Products Inc. 1020 S. Main St., P.O. Box 2948 Kokomo, IN 46904-2948 765-457-1194 fax, 765-457-1196

Plating Research Inc. 179 Fern Rd. E. Brunswick, NJ 08816 732-651-0818

Plating Resources Inc. 2030 Midway Dr. Twinsburg, OH 44087 330-963-6360 fax, 330-963-6362

Plating Specialists Inc. 18 N. Ft. Thomas Ave., Ste. 3C Ft. Thomas, KY 41075 606-441-9500 fax, 606-441-2447

Plating Supplies International Inc. 630 Silver St., P.O. Box 363 Agawam, MA 01001 413-786-2020 fax, 413-789-3373

Plating Systems & Technologies Inc. 317 N. Mechanic St. Jackson, MI 49201 517-783-4776 fax, 517-783-5875
(*See our ad on page 409.*)

Plating Technology Equipment Div. 1415 S. 22nd St., P.O. Box 06236 Columbus, OH 43206 614-444-8693 fax, 614-444-2045

Plating Test Cell Supply Co. 948-B Wayside Rd. Cleveland, OH 44110 216-486-8400 fax, 216-486-8555
(*See our ad on page 595.*)

Platt Bros. & Co. 2670 S. Main St. Waterbury, CT 06721 203-753-4194 800-752-8276 fax, 203-753-9709

PKG Equipment Inc. 367 Paul Rd. Rochester, NY 14624 716-436-4650 fax, 716-436-3751

PMS Inc. 32043 Howard St. Madison Heights, MI 48071 248-588-6500 fax, 248-585-8636

Polaris Plastics Inc. 18704 S. Ferris Pl. Rancho Dominguez, CA 90220 310-537-2300 800-888-8985 fax, 310-537-7770

Pollution Application Systems Co. Inc. The Byrne Bldg., 200 Lincoln Ave., Ste. 12 Phoenixville, PA 19460 610-983-9585 800-548-2545 fax, 610-983-3913

Poly Processing Co. P.O. Box 4150 Monroe, LA 71211 318-343-7565 fax, 318-343-8795

Poly Products Corp. 777 E. 82nd St. Cleveland, OH 44103-1817 216-391-7659 fax, 216-881-8991
(*See our ad on page 831.*)

Poly-Bond Mfg. Co. 16525 Van Dam Rd. South Holland, IL 60473 708-331-6232 800-395-6232 fax, 708-331-0526

Polyfab Plastics & Supply 820 N. Cedarbrook Springfield, MO 65802 417-862-6512 fax, 417-862-9080

Polyflow Inc. 100 Pratt's Junction Rd. Sterling, MA 01564 978-422-6708 fax, 978-422-0008

Polylonix Separation Technologies Inc. 2351 U.S. Rte. 130, P.O. Box 1004 Dayton, NJ 08810-1004 732-274-3103 888-249-4469 fax, 732-274-3144

Potters Industries Inc., An Affiliate of the PQ Corp. Southpoint Corporate Headquarters, P.O. Box 840 Valley Forge, PA 19482-0840 610-651-4700 fax, 610-408-9723
(*See our ad on page 103.*)

Power Conversion Corp. P.O. Box 2793 Plainfield, NJ 07062 908-757-1323 fax, 908-757-1222

Power Flame Inc. 2001 S. 21st St. Parsons, KS 67357 316-421-0480 fax, 316-421-0948

Power Plant Service Inc. 2500 W. Jefferson Blvd. Fort Wayne, IN 46802 219-432-6716 fax, 219-436-3340

Power Sonics LLC 5320 Enterprise St. Eldersburg, MD 21784-9354 410-552-1011 fax, 410-552-1396

Praxair Surface Technologies Inc. 1555 Main St. Indianapolis, IN 46224 317-240-2650 fax, 317-240-2225

Precious Metals Processing Consultants Inc. 430 Bergen Blvd. Palisades Park, NJ 07650 201-944-8053 fax, 201-944-8003
(*See our ad on page 833.*)

Precise Filtration Products Inc. 3010 Deli St., N.E. Grand Rapids, MI 49505 616-363-0051 fax, 616-363-0052

Precision Finishing Inc. 708 Lawn Ave., P.O. Box 272 Sellersville, PA 18960 215-257-6862 800-523-6232 fax, 215-257-4162

Precision Plus Vacuum Parts Inc. 2055 Niagara Falls Blvd. Niagara Falls, NY 14304 716-297-2039 800-526-2707 fax, 716-297-8210

Precision Process Equipment Inc. 2221 Niagara Falls Blvd. Niagara Falls, NY 14304 716-731-1587 800-707-3433 fax, 716-731-1591
(*See our ad on page 643.*)

Precision Quincy Corp. 1625 W. Lake Shore Dr. Woodstock, IL 60098 815-338-2675 800-338-0079 fax, 815-338-2960
(*See our ad on page 634.*

Preferred Tape Inc. 3148 S. 108th E. Ave., Ste. 110 Tulsa, OK 74146 918-665-2919 fax, 918-665-2918

Premier Services Corp. 7251 Engle Rd., Ste. 415 Middleburg Heights, OH 44130 216-234-4600 800-227-4287 fax, 216-234-5772

Pressure Blast Mfg. Co. Inc. 41 Chapel St. Manchester, CT 06040 860-643-2487 800-722-5278 fax, 860-645-6257

Pressure Island 3345 Edison Way Menlo Park, CA 94025 650-780-7900 fax, 650-780-9988

Price Industries Inc. 3286 Industrial Dr., S.E. Dutton, MI 49316 616-698-0300 fax, 616-698-0830

Pro EP 2161 Demington Dr. Cleveland, OH 44106 216-397-1390 fax, 216-397-9907
(*See our ad on page 448.*)

Pro Rac Co. Inc. Highway 64 E., P.O. Box 208 Lawrenceburg, TN 38464 615-762-6507 fax, 615-766-1746

Pro-Fab Mfg. Inc. 837 E. Highland Rd. Macedonia, OH 44056 216-468-2300 800-441-3584 fax, 216-468-2323

Proceco Inc. 14790 St. Augustine Rd. Jacksonville, FL 32258-4407 904-886-0200 800-978-6677 fax, 904-886-0232

Proceco Ltd. 7300 Tellier St. Montreal, Que. H1N 3T7, Canada 514-254-8494 fax, 514-254-6922
(*See our ad on page 125.*)

Procedyne Corp. 11 Industrial Dr. New Brunswick, NJ 08901 732-249-8347 fax, 732-249-7220

Process Chiller Systems Inc. 5293 Harborside Dr.. Tampa, FL 33615 813-818-1888 fax, 813-854-3403

Process Electronics Corp. 105 Wolfpack Dr., P.O. Box 12000 Gastonia, NC 28053 704-864-9704 800-421-9107 fax, 704-861-0264
(*See our ad on page 697.*)

Process Technology Inc. 7010 Lindsay Dr., P.O. Box 660 Mentor, OH 44061 440-946-9500 800-621-1998 fax, 440-974-9561
(*See our ad on the Inside Back Cover.*)

Prochemtech Intl. Inc. RD #2, Box 282 Brockway, PA 15824 814-265-0959 fax, 814-265-1263

ProdEcon Inc. 120 Morton Mill Cir. Nashville, TN 37221 615-673-2297 fax, 615-673-2294

Production Concepts Inc. 714 Hickory Rd. Woodstock, IL 60098 815-338-0485 800-475-1178 fax, 815-338-0496

Progressive Recovery Inc. 700 Industrial Dr. Dupo, IL 62239 618-281-7196 fax, 618-286-5009

Progressive Technologies 4201 Patterson, S.E. Grand Rapids, MI 49512-4105 616-957-0871 fax, 616-957-3484

Proheatco Mfg. Co. 3427 Pomona Blvd., Unit D Pomona, CA 91768 909-598-7445 800-423-4195

Prolite Plastics Ltd. 1620 Kingsway Ave. Port Coquitlam, B.C. V3C 3Y9, Canada 604-944-6260 fax, 604-944-8854

ProMinent Fluid Controls Inc. 136 Industry Dr. Pittsburgh, PA 15275-1014 412-787-2484 fax, 412-787-0704

Prosco Inc. 3818 E. Prospect Indianapolis, IN 46203 317-353-2920 fax, 317-353-0733

Prosys Corp. 187 Billerica Rd. Chelmsford, MA 01824 978-250-4940 800-370-7767 fax, 978-250-4977
(*See our ad on page 809.*)

Protech Floorings & Linings Inc. P.O. Box 2434 Green Bay, WI 54306-2434 920-435-6792 fax, 920-435-7094

Protective Closures Co. Inc., Caplugs Div. 2150 Elmwood Ave. Buffalo, NY 14207 716-876-9855 fax, 716-874-1680

Protectoseal Co. 225 W. Foster Ave. Bensenville, IL 60106-1690 630-595-0800 800-323-2268 fax, 708-595-8059

Protherm Mfg. Co. 1233 W. Collins Ave. Orange, CA 92667 714-538-7492 fax, 714-538-8746

Pulsafeeder Inc., A Unit of Idex 27101 Airport Rd. Punta Gorda, FL 33982 941-575-3800 800-426-8164 fax, 941-575-4085

Pulse Instruments 6411 Independence Ave. Woodland Hills, CA 91367 818-348-8090 800-462-1926 fax, 818-348-8990

Puma Chemical P.O. Box 67 Warne, NC 28909 828-389-3074 800-211-7993 fax, 828-389-4023
(*See our ad on page 197.*)

Pumper Parts LLC 6014 Enterprise Dr. Export, PA 15632 724-387-1776 877-786-7548 fax, 724-387-1774
(*See our ad on page 744.*)

Purac Engineering Inc., Div. of Anglian Water 5301 Limestone Rd., Ste. 126 Wilmington, DE 19808 302-239-9431 fax, 302-239-9085

Pure Cycle Environmental Technologies 20 Wilbraham St. Palmer, MA 01069 413-283-8939 fax, 413-283-4480

Pure Tech Inc. Commerce Dr., P.O. Box 1319 Carmel, NY 10512 914-878-4499 fax, 914-878-4727

Purolite Co. 150 Monument Rd. Bala Cynwyd, PA 19004-1702 610-668-9090 800-343-1500 fax, 610-668-8139
(*See our ad on page 833.*)

Pylam Products Co. Inc. 1001 Stewart Ave. Garden City, NY 11530 516-222-1750 fax, 516-222-1988

Q

Q-Panel Lab Products 26200 First St. Westlake, OH 44145 440-835-8700 fax, 440-835-8738

QVF Process Systems Inc. 224 N. Main St., Bldg. F, Sect. 4 Horseheads, NY 14845-1766 607-796-4800 fax, 607-739-6717
(*See our ad on page 818.*)

Quaker Chemical Corp. Elm and Lee Sts. Conshoken, PA 19428-0809 610/832-4000 fax, 610/832-4495

R

R-V Industries Inc. 584 Poplar Rd. Honey Brook, PA 19344 610-273-2457 800-733-7844 fax, 610-273-3361
(*See our ad on page 805.*)

R.J. Coatings Inc./Michrome Inc. 8825 Grinnell Ave. Detroit, MI 48213 313-267-5200 fax, 313-924-8910

REM Chemicals Inc. 325 W. Queen St. Southington, CT 06489 860-621-6755 fax, 860-621-8822

REM Sales Inc., Pero Parts Cleaning Systems 34 Bradley Park Rd. East Granby, CT 06026 860-653-0071 fax, 860-653-0393

RGF Environmental Systems Inc. 3875 Fiscal Ct. West Palm Beach, FL 33404 561-848-1826 800-842-7771 fax, 561-848-9454

RRC Agmet Inc. 50 Howe Ave. Millbury, MA 01527 508-865-4451 fax, 508-865-1853

Racal Health & Safety Inc. 7305 Executive Way Frederick, MD 21701-8368 301-695-8200 800-682-9500 fax, 301-695-4413

Rack Processing Co. 2350 Arbor Blvd. Dayton, OH 45439 937-294-1911 fax, 937-294-7153

Ramco Equipment Corp. 32 Montgomery St. Hillside, NJ 07205 908-687-6700 800-553-3650 fax, 908-687-0653

Rand-Bright Corp. 2940 S. 166th St. New Berlin, WI 53151 414-784-1978 fax, 414-782-6902

Rapid Power Technologies Inc. 18 Old Graysbridge Rd., P.O. Box 291 Brookfield, CT 06804 203-775-0411 800-332-1111 fax, 203-775-0666
(*See our ad on page 683.*)

Raschig Corp. 5000 Old Osborne Tpk., P.O. Box 7656 Richmond, VA 23231 804-222-9516 fax, 804-226-1569

Rasco Inc. 1635-2 Woodside Dr. Woodbridge, VA 22191-3045 703-643-2952 800-899-2952 fax, 703-497-2905

Raytech Industries, A Div. of Lyman Products Corp. 475 Smith St. Middletown, CT 06457 860-632-2020 800-243-7163 fax, 860-632-1699

Recontek Inc. RR 2, U.S. Rte. 36, P.O. Box 379 Newman, IL 61942 217-837-2461 fax, 217-837-2362

Recovery Engineering & Sales Co. Inc. P.O. Box 297 Arvada, CO 80001-0297 303-292-5702 fax, 303-292-5717
(*See our ad on page 837.*)

Rectifiers & Plating Equipment Ltd. 31 Leading Rd. Rexdale, Ont. M9V 4B7, Canada 416-744-7848 fax, 416-744-1169

Red Bird Service 205 Western Ave., P.O. Box 155 Osgood, IN 47037 812-689-4040 800-428-3502 fax, 812-689-4061
(*See our ad on page 521.*)

Redring Electric Co. 829 Highams Court Woodbridge, VA 22191 703-491-1181 800-435-4644 fax, 703-491-8831

Refining Systems Inc. P.O. Box 72466 Las Vegas, NV 89170 702-368-0579 fax, 702-368-0933

Reliable Buff Co. 226 Bivens Rd., P.O. Box 942 Monroe, NC 28011 704-289-4300 800-338-2833 fax, 704-283-9507

Reliable Equipment Corp. 633 Richmond St., N.W. Grand Rapids, MI 49504 616-363-4823 fax, 616-363-3101

Reliable-West Tech Inc. 302 Platts Mill Rd., P.O. Box 1303 Naugatuck, CT 06770 203-574-4963 800-906-5338 fax, 203-597-0167

Remco Engineering 4193 Carpinteria Ave., Unit 4 Carpinteria, CA 93109 805-566-9262 fax, 805-566-2962

Renovare International Inc. 1401 N. Broadway, Ste. 225 Walnut Creek, CA 94596 925-945-7576 fax, 925-945-0131

Republic Metals Inc. 7930 Jones Rd., P.O. Box 605217 Cleveland, OH 44105 216-641-2575 888-877-1726 fax, 216-641-5408
(*See our ad on page 225.*)

Research & PVD Materials Corp. P.O. Box 4796 Wayne, NJ 07474-4796 973-575-4245 fax, 973-575-6460

Research Inc. 6425 Flying Cloud Dr. Eden Prairie, MN 55344 612-941-3300 fax, 612-941-3628

ResinTech Inc. 1980 Old Cuthbert Rd. Cherry Hill, NJ 08034 609-354-1152 fax, 609-354-6337

Responsible Alternatives Inc. 4027 Colonel Glenn Hwy. Dayton, OH 45431-1672 937-253-4789 fax, 937-427-1242

Rex-Cut Products Inc. 960 Airport Rd., P.O. Box 2109 Fall River, MA 02772 508-678-1985 800-225-8182 fax, 800-638-8501

Rhone-Poulenc Basic Chemicals Co. P.O. Box 1130 Nashville, TN 37202 615-386-7888 fax, 615-386-7822

Richard Tscherwitschke GmbH, Kunststoff-Apparatebau und Ablufttechnik Dieselstr. 21, Leinfelden-Echterdingen D-70771, Germany 49 711 795 061 fax, 49 711 797 0236

Richcraft Designs Inc. 220 26th St. Bay City, MI 48708 517-892-8237 fax, 517-892-8235

Richwood Industries 12700 Knott Ave., Bldg. A Huntington Beach, CA 92649 714-892-8100 fax, 714-892-8818
(*See our ad on page 119.*)

Riedel-de Haén D-30918 Seelze Germany 49 513 799 9225 fax, 49 513 799 9107

Rin Inc. 4831 S. Whipple Chicago, IL 60632 773-523-0784 fax, 773-523-7838
(*See our ad on page 16.*)

Rit-Chem Co. Inc. 109 Wheeler Ave., P.O. Box 435 Pleasantville, NY 10570 914-769-9110 fax, 914-769-1408

Rivas Co., Fred B. P.O. Box 67 Tuckerton, NJ 08087 609-296-8283 800-233-7176

Roberts Chemicals Co. Inc. 1 Virginia Ave. Providence, RI 02905 401-781-1221 fax, 401-781-1412

Robicon 500 Hunt Valley Dr. New Kensington, PA 15068 412-339-9500 fax, 412-339-8100

Rochester Midland Corp. P.O. Box 1515 Rochester, NY 14603-1515 716-333-2200 fax, 716-467-4406

Röchling Engineered Plastics P.O. Box 2729 Gastonia, NC 28053 704-922-7814 800-541-4119 fax, 704-922-7651

Roesler Metal Finishing USA LLC 4407 W. Columbia Ave. Battle Creek, MI 49015 616-441-3000 fax, 616-441-3001
(*See our ad on page 111.*)

Rohm & Haas Co. Independence Mall, W. Philadelphia, PA 19105 215-592-3000 fax, 215-592-3377

Roilgard Inc. 5600 13th St. Menominee, MI 49858-1029 906-863-4401 800-338-9886 fax, 906-863-5889

Romanoff International Supply Corp. 9 Deforest St. Amityville, NY 11701 631-842-2400 800-221-7448 fax, 631-842-0028

Romar Technologies Inc. 94 Central St. Topsfield, MA 01983 978-887-0777 fax, 978-887-0111

Ronalco Inc. 1600 Northwestern Pkwy. Louisville, KY 40203 502-584-7772 fax, 502-584-0976

Ronningen-Petter 9151 Shaver Rd., P.O. Box 188 Portage, MI 49081-0188 616-323-1313 800-656-3344 fax, 616-323-0065

Röntgenanalytik Messtechnik GmbH Georg-Ohm-Str. 6 Taunusstein, D-65232, Germany 49 612 871 080 fax, 49 612 873 601

Rosemont Analytical 1201 N. Main St. Orrville, OH 44687 330-682-9010 800-628-1200 fax, 330-684-4419

Rosemont Industries Inc. 1700 West St. Cincinnati, OH 45215 513-733-4277 800-782-9958 fax, 513-733-9165

Rosemount Analytical, Uniloc Div. 2400 Barranca Pkwy. Irvine, CA 92714 714-863-1181 fax, 714-474-7250

RotaDyne, Engineered Roller Div. 10722 Bennett Rd. Dunkirk, NY 14048 716-366-7401 fax, 716-366-7402

Roto-Finish Co. Inc. 1600 Douglas Ave. Kalamazoo, MI 49007-1690 616-327-7071 800-992-1417 fax, 616-345-1710

Roto-Jet of America Co. Inc. 26943 Ruether Ave., Unit S Santa Clarita, CA 91351 805-299-2231 fax, 805-299-9239

Roto-Magic Mfg. Inc. 290 Smith St. Providence, RI 02908-4997 401-455-8300 800-556-6496 fax, 401-455-8305

Ruthman Pump & Engineering Inc. 22 Ruthman Dr. Dry Ridge, KY 41035 606-824-5001 fax, 606-824-3011

Ryan Herco Products Corp. 3010 N. San Fernando Blvd., P.O. Box 588 Burbank, CA 91503 818-841-1141 800-848-1141 fax, 818-973-2600

S

S&K Products International 80 Red Schoolhouse Rd., Unit 102 Chestnut Ridge, NY 10977 914-425-6200 fax, 914-425-6670

S&K Reagents Inc. 619 E. Jewell Ave. Denver, CO 80210 303-777-0731 fax, 303-777-0731

S&S Industrial Services 1345 Pearl St. Waukesha, WI 53186 414-548-8040 fax, 414-548-8049

SEPR Ceramic Beads & Powders 1122 Rte. 22 Mountainside, NJ 07092 908-654-0660 fax, 908-654-0669

SMI Div., Sohn Mfg. Inc. 544 Sohn Dr. Elkhart Lake, WI 53020 920-876-3365 fax, 920-876-2952

SPF Corp. of America 1812 Boxelder St. Louisville, CO 80027-3008 303-665-6222 fax, 303-665-8335

Sabin Metal Corp. 300 Pantigo Pl., Ste. 102 East Hampton, NY 11937 631-329-1717 fax, 631-329-1985

Safety-Kleen Corp. 1000 N. Randall Rd. Elgin, IL 60123 847-697-8460 800-323-5040 fax, 847-468-8515

Salem Environmental 13700 W. Buena Vista Detroit, MI 48227 313-837-7711

Samsco Inc. 18 Cote Ave. Goffstown, NH 03045 603-668-7111 fax, 603-647-0537
(See our ad on page 829.)

Sanborn Technologies, A Waterlink Co. 9 Industrial Park Rd. Medway, MA 02053-1732 508-533-8800 800-343-3381 fax, 508-533-1440

Sanchem Inc. 1600 S. Canal St. Chicago, IL 60616 312-733-6111 800-621-1603 fax, 312-733-7432

Sanda Corp. 4005 Gypsy Ln. Philadelphia, PA 19144 215-849-8100 800-999-2993 fax, 215-849-8102
(See our ad on page 521.)

Sanford Process Corp. 65 North Ave. Natick, MA 01760 508-653-7860 fax, 508-653-7832

SanRex Corp. 50 Seaview Blvd. Port Washington, NY 11050 516-625-1313 fax, 516-625-8845

Sara Glove Co. Inc. 117 Benedict St., P.O. Box 1940 Waterbury, CT 06722-1940 203-574-4090 fax, 203-574-3500

Saranac Tank Inc. 100 W. Main St., P.O. Box 176 Saranac, MI 48881 616-642-9481 fax, 616-642-9377

Savitt Industrial Products Inc. P.O. Box 248 Brick, NJ 08723 732-972-0016

Sawyer and Smith Corp. 3430 Krather Rd. Cleveland, OH 44109-3126 216-459-2209 fax, 216-7490087

Schaffner Mfg. Co. Inc. 21 Herron Ave. Pittsburgh, PA 15202 412-761-9902 fax, 412-761-8998
(See our ads on pages 51, 55, 71.)

Schlotter, Dr. Ing. Max Postfach 1452 Geislingen, D-73312 Germany 49 733 120 50 fax, 49 733 120 5123

Schneider and Associates Inc., John 10620 N. Port Washington Rd. Mequon, WI 53092 414-241-3200 fax, 414-241-8712

Schwartz Chemical Co. Inc. 50-01 2nd St. Long Island City, NY 11101 718-784-7595 fax, 718-784-7635

Scientific Control Laboratories Inc. 3158 S. Kolin Ave. Chicago, IL 60623 773-254-2406 fax, 773-254-6661

ScrubAir Vent Systems Inc. 1220 Karl Ct. Wauconda, IL 60084 847-526-5172 fax, 847-526-6278
(See our ad on page 785.)

Seasafe Inc. 100 Capitol Dr., Ste. 210 Lafayette, LA 70508 318-234-5059 800-326-8842 fax, 318-234-7758

Seiler Hughes 138 W. Barney St. Baltimore, MD 21230 410-727-6770 fax, 410-332-9936

Seleco Inc. P.O. Box 68809 Indianapolis, IN 46268 317-872-4148 fax, 317-875-3276

Sensorex Inc. 11751 Markon Dr. Garden Grove, CA 92842 714-895-4344 fax, 714-894-4839
(See our ad on page 604.)

Separation Dynamics Inc. 1328 Wheaton Dr. Troy, MI 48083 248-680-0088 fax, 248-680-0044

Separation Technologists Inc. 100 Griffen Brook Park Methuen, MA 01844 978-794-1170 fax, 978-794-0933

Seprotech Systems Inc. 2378 Holly Ln. Ottawa, Ont. K1V 7P1, Canada 613-523-1641 fax, 613-731-0851

Sequel Corp. 119 N. Jonathan Blvd. Chaska, MN 55318-2395 612-448-3870 800-553-8273 fax, 612-448-3848
(See our ad on page 491.)

Sequoia Corp. 4009 Renate Dr. Las Vegas, NV 89103 702-253-1891 800-323-9811 fax, 702-253-1894

Serec Corp. 335 Valley St., P.O. Box 28129 Providence, RI 02908 401-421-6080 fax, 401-521-5690

SERFILCO Ltd. 1777 Shermer Rd. Northbrook, IL 60062-5360 847-559-1777 800-323-5431 fax, 847-559-1995
(See our ads on pages 717, 735.)

Sermatech International Inc. 155 S. Limerick Rd. Limerick, PA 19468 610-948-5100 fax, 610-948-2771

Servi-Sure Corp. 2020 W. Rascher Ave. Chicago, IL 60625 773-271-5900 fax, 773-271-3777
(See our ad on page 487.)

Sethco Div., Met-Pro Corp. 70 Arkay Dr., P.O. Box 12128 Hauppauge, NY 11788-3773 631-435-0530 fax, 631-435-0654
(See our ads on pages 721, 723, 744, 745.)

Sherburne Metal Products Inc. Two Greenwich Plaza, Ste. 100 Greenwich, CT 06830 203-622-3920 fax, 203-622-3916

Shercon Inc. 10425 Slusher Dr., P.O. Box 2787 Santa Fe Springs, CA 90670 562-946-8555 800-228-3218 fax, 562-946-1015

Shields Co. 1891 Goodyear Ave., Unit 604, P.O. Box 1572 Ventura, CA 93002 805-642-4408 800-799-4408 fax, 805-642-4417

Shipley Ronal 455 Forrest St. Marlborough, MA 01752-3001 508-481-7950 800-743-9865 fax, 508-481-7950
(See our ad on page 1.)

Shipley Ronal 272 Buffalo Ave. Freeport, NY 11520 516-868-8800 fax, 516-868-8824
(See our ad on page 1.)

Siebec 8 Rue Guy Mocquet, B.P. 88 Fontaine Cedex, 38602, France 33 4 76 26 12 09 fax, 33 4 76 27 04 82

Sifco Selective Plating, Div. of Sifco Industries Inc. 5708 Schaaf Rd. Cleveland, OH 44131 216-524-0099 fax, 216-524-6331
(*See our ads on pages 363, 373.*)

Sil-trade USA Inc. 173 Ridgedale Ave., P.O. Box 1332 Morristown, NJ 07962-1332 973-889-9100 fax, 973-889-9112

Singleton Corp. 3280 W. 67th Pl. Cleveland, OH 44102 216-651-7800 fax, 216-651-4247
(*See our ads on pages 343, 587, 631.*)

Sintex Minerals Services Inc. 2500 Wilcrest, Ste. 300 Houston, TX 77042 713-954-4805 fax, 713-954-4802

Sirius Technology Inc. 132 Clear Rd. Oriskany, NY 13424 315-768-6635 fax, 315-768-3561

Smith Precious Metals Co. 5 Virginia Ave. Providence, RI 02905 401-467-5025 fax, 401-461-1740

Snyder Filtration 4971 Allison Pkwy., Ste. A Vacaville, CA 95688 707-451-6060 fax, 707-451-6064

Snyder General Corp., American Air Filter P.O. Box 35690 Louisville, KY 40232 502-637-0011 fax, 502-637-0148

Sogem-Afrimet Inc. 1212 Ave. of the Americas New York, NY 10036 212-403-3214 fax, 212-764-8851

Solar Products Inc. 5 Colton Rd. E. Lyme, CT 06333 860-739-2901 800-616-2601 fax, 860-739-2905

Soleras Ltd. 589 Elm St., P.O. Box BC Biddeford, ME 04005 207-282-5699 fax, 207-284-6118

Solmetex 29 Cook St. Billerica, MA 01821 978-262-9890 fax, 978-262-9889

Solvay Interox Inc. 3333 Richmond Ave. Houston, TX 77227 713-525-4000 800-468-3769 fax, 713-525-7886

Solvent Kleene Inc. 131½ Lynnfield St. Peabody, MA 01960 978-531-2279 fax, 978-532-9304

Sonic Air Systems Inc. 4111 N. Palm St. Fullerton, CA 92835 714-870-2700 800-827-6642 fax, 714-870-0100

Sonicor Instrument Corp. 100 Wartburg Ave. Copiague, NY 11726 631-842-3344 fax, 631-842-3389
(*See our ad on page 167.*)

Sorbent Control Technologies Inc. 1021 Davis Rd. Elgin, IL 60123 847-695-2900 fax, 847-695-2939

South Florida Test Service, Div. of Atlas Electric Devices Co. 17301 Okeechobee Rd. Miami, FL 33015 305-824-3900 fax, 305-362-6276

Southeastern Chemical 1607 Camden St. Chattanooga, TN 37406 423-662-5154 fax, 423-698-5152

Southeastern Rack Co. 1245 16th St. Vero Beach, FL 32960 561-567-2262 fax, 561-567-2640

Southern Industrial Chemicals Inc. 1450 Marietta Blvd., N.W., P.O. Box 93069 Atlanta, GA 30377-3069 404-351-9770 800-394-9770 fax, 404-351-9887
(*See our ad on page 493.*)

Southwest United Industries Inc. 422 St. Louis St. Tulsa, OK 74120 918-587-4161 fax, 918-582-6158

Southwestern Rack Co. 1400 Royal Pkwy. Euless, TX 76040 817-540-3800 fax, 817-354-5423

Spang Power Electronics 5241 Lake St., P.O. Box 457 Sandy Lake, PA 16145 724-376-7515 800-223-4469 fax, 724-376-2249

Spartan Felt Co. P.O. Box 1932 Spartanburg, SC 29304 864-576-7919 fax, 864-574-4507
(*See our ad on page 59.*)

Spears Mfg. Co. 15860 Olden St. Sylmar, CA 91342 818-364-1611 800-862-1499 fax, 818-367-3014

Special Chemicals Inc. 364 Palisade Ave., Apt. 4E Cliffside Park, NJ 07010 201-313-1029 fax, 201-313-1625

Special Masking 5618 Hamlet Ave. Cleveland, OH 44127 216-441-5244 800-433-2719 fax, 216-441-0715

Special Plastic Systems Inc. 914 Westminster Ave. Alhambra, CA 91803 626-570-8320 800-423-4422 fax, 626-570-6058

Specialty Chemical Industry Corp. 2300 Lincoln Park, W., Ste. A-10 Chicago, IL 60614 312-880-1786 fax, 312-880-1911

Specialty Plastic Fabricators Inc. 9658 W. 196th St. Mokena, IL 60448 708-479-5501 800-747-9509 fax, 708-479-5598
(*See our ad on page 669.*)

Specialty Tapes, Div. of RSW Inc. 4221 Courtney Rd. Franksville, WI 53126 414-835-0748 800-545-8273 fax, 414-835-0749

Specialty Testing & Development Co. P.O. Box 126 Jacobus, PA 17407 717-428-3491 fax, 717-428-3491

Spectra Precision 911 Hawthorne Dr. Itasca, IL 60143 630-285-1400 fax, 630-285-1410

Spectro Wire & Cable Inc. P.O. Box 6297 Moore, OK 73153 800-255-6371 fax, 405-799-1685

Sperry & Co., D.R. 112 N. Grant St. N. Aurora, IL 60542 630-892-4361 888-997-9297 fax, 630-892-1664
(*See our ad on page 719.*)

Spraying Systems Co. North Ave. & Schmale Rd., P.O. Box 7900 Wheaton, IL 60189-7900 630-665-5000 800-957-7729 fax, 630-260-0842

Sputtering Materials Inc. 7950 Sugar Pine Ct. Reno, NV 89523 702-787-6700 fax, 702-787-2663

Stablex, Canada Inc. 760 Industrial Blvd. Blainville, Que. J7C 3V4, Canada 514-430-9230 800-782-2539 fax, 514-430-4642

Stan Sax Corp. 101 S. Waterman St. Detroit, MI 48209-3091 313/841-7170 fax, 313/841-7171
(*See our ads on the Inside Front Cover and pages 55, 59.*)

Standard Abrasives Inc. 4201 Guardian St. Simi Valley, CA 93063 805-520-5800 800-423-5444 fax, 805-520-5828

Stapleton Technologies 1350 W. 12th St. Long Beach, CA 90813 562-437-0541 800-266-0541 fax, 562-437-8632

Star Systems Filtration Div., Hilliard of South Carolina Inc. 101 Kershaw St., P.O. Box 518 Timmonsville, SC 29161 843-346-3101 800-845-5381 fax, 843-346-3736

Starline Products 2226 Castle Harbor Pl., S. Ontario, CA 91761 909-930-5535 800-523-8674 fax, 909-930-5540

Starlite Technical Service Inc. 1319 W. North Ave. Chicago, IL 60622 773-772-2278 fax, 773-772-5870
(*See our ad on page 331.*)

Steelcraft Corp. P.O. Box 12748 Memphis, TN 38182-0748 901-452-5200

Steelman Industries Inc. 2706 Hwy. 135, P.O. Box 1461 Kilgore, TX 75663 903-984-3061 800-227-5827 fax, 903-984-1384
(*See our ad on page 637.*)

Stein & Associates Inc., Norman P.O. Box 331 New Haven, IN 46774 219-420-4000 fax, 219-420-4100

Steinen Mfg. Co., Wm. 29 E. Halsey Rd. Parsippany, NJ 07054 973-887-6400 fax, 973-887-4632

Stellar Solutions Inc. 1000 N. Harrison St. Algonquin, IL 60102-2314 847-854-2800 fax, 847-854-2830

Sterling Systems Sales Corp. 3745 Stern Ave. St. Charles, IL 60174 630-584-3580 800-888-2541

Sternvent Co. Inc. 253 W. Fort Lee Rd. Bogota, NJ 07603 201-488-1146 fax, 201-488-1605

Stewart Technologies Inc. 3342 E. Wier Ave. Phoenix, AZ 85040 602-232-0075 fax, 602-232-6076
(*See our ad on page 647.*)

StockCap, A Sinclair & Rush Co. 13515 Barrett Pkwy. Dr. St. Louis, MO 63021-5880 314-984-8100 800-827-2277 fax, 314-984-0021
(*See our ad on page 227.*)

Stokes Vacuum Inc. 5500 Tabor Rd. Philadelphia, PA 19120 215-831-5400 888-478-6537 fax, 215-831-5420

Stone Chemical Co. 1176 Hyde Park Ln. Naperville, IL 60565 630-305-0538 fax, 630-305-0825
(*See our ad on page 491.*)

Straus Chemical Corp. 2014 E. Devon Ave. Elk Grove Village, IL 60007 847-640-1600 fax, 847-640-1699

Stutz Co. 4450 W. Carroll Ave. Chicago, IL 60624 773-287-1068 800-466-0442 fax, 773-287-4303

Summit Process Consultants Ltd. 1863 N. Wabash St. Wabash, IN 46992 219-563-7783

Summit Scientific Corp. 31 Dwight Pl. Fairfield, NJ 07006 973-227-6190 800-631-0459 fax, 973-227-3538

Sumrack Equipment and Supply Co. Inc. (SESCO) 655-A McCormick Dr. Lapeer, MI 48446 810-667-9994 fax, 810-667-9988

Sunbelt Systems 1112 Luke St. Irving, TX 75061 972-790-5300 fax, 972-790-8953

Supfina Machine Co. Inc. 33 Plan Way, Bldg. 1 Warwick, RI 02886 401-738-4010 fax, 401-738-4266

Sur-Fin Chemical Corp. 1530 Spence St. Los Angeles, CA 90023 213-262-8108 800-282-3533 fax, 213-264-7734

Surface Automation Systems LLC 002 84th St., S.W. Byron Center, MI 49315 616-827-1011 fax, 616-827-1015

Surface Science Western Rm. G1, Western Science Centre, University of Western Ontario London, Ont. N6A 5B7, Canada 519-661-2173 fax, 519-661-3709

Surface Technology Inc. P.O. Box 8585 Trenton, NJ 08650 609-259-0099 800-530-1398 fax, 609-259-0077
(*See our ad on page 433.*)

SurfTran, Div. of Robert Bosch Corp. 30250 Stephenson Hwy. Madison Heights, MI 48071 248-547-3133 fax, 248-547-0206

Sweco Inc. 7120 Buffington Rd., P.O. Box 1509 Florence, KY 41042 606-727-5147 800-849-3259 fax, 606-727-5122

Sweet Chemical Services Co. Inc. 1440 E. Cliff Rd. Burnsville, MN 55337 612-890-3923 800-606-9371 fax, 612-890-1799

Swest Inc. 11090 N. Stemmons Fwy. Dallas, TX 75229 972-247-7744 800-527-5057 fax, 972-247-3507
(*See our ad on page 257.*)

Sybron Chemicals Inc. Birmingham Rd. Birmingham, NJ 08011 609-893-1100 800-678-0020 fax, 609-894-8641
(*See our ad on page 833.*)

Systematics Inc. 26 Burnside St. Bristol, RI 02809 401-253-0050 fax, 401-253-1602
(*See our ad on page 583.*)

SystemOne Technologies Inc. 8305 N.W. 27th St. Miami, FL 33122 305-593-8015 800-711-1414 fax, 305-593-8016
(*See our ad on page 127.*)

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TBI-Bailey Controls Co. 2175 Lockheed Way Carson City, NV 89706 702-883-4366 fax, 702-883-4373

TDK Ohio Corp. 11288 Alameda Dr. Strongsville, OH 44136 216-572-4988 fax, 216-572-9140

TFS Technologies 5604 Wilshire Ave., N.E. Albuquerque, NM 87109 505-856-1480 800-795-7977 fax, 505-856-1478

Taber Industries 455 Bryant St. N. Tonawanda, NY 14120 *716-694-4000 800-333-5300 fax, 716-694-1450*

Tafa Inc. 146 Pembroke Rd. Concord, NH 03301 603-224-9585 fax, 603-225-4342

Talisman Partners Ltd. 5460 S. Quebec St., Ste. 100 Englewood, CO 80110-1916 303-771-3101 fax, 303-771-3194

Tally Cleaning Systems, METFAB Engineering 332 John L. Dietsch Blvd. Attleboro Falls, MA 02763 508-695-1007 fax, 508-695-6335

Tally Metal Sales Inc. 1850 Johns Dr. Glenview, IL 60025 847-729-8822 800-323-1310 fax, 847-729-1564
(*See our ads on pages 277, 329.*)

Target Materials Inc. 1145 Chesapeake Ave. Columbus, OH 43212 614-486-7055 800-292-8639 fax, 614-486-0912

Tarus Equipment Co. P.O. Box 14709 Columbus, OH 43214 614-431-1241 800-634-2969 fax, 614-431-5775

Taskem Inc. 4639 Van Epps Rd. Brooklyn Heights, OH 44131 216-351-1500 fax, 216-351-5677
(*See our ads on pages 329, 808.*)

Taylex Group P.O. Box 36308 Indianapolis, IN 46236 317-823-7448 fax, 317-823-7448

Tech Systems Inc. 1030 N. Lincoln St., P.O. Box 485 Greensburg, IN 47240 812-663-4720 fax, 812-663-4799

Techne Inc. 3700 Brunswick Pike Princeton, NJ 08540 609-452-9275 fax, 609-987-8177

Technic Inc. One Spectacle St., P.O. Box 9650 Providence, RI 02904 401-781-6100 fax, 401-781-2890
(*See our ads on pages 259, 299, 429.*)

Technic Inc., Equipment Div. 55 Maryland Ave. Pawtucket, RI 02860 401-728-7081 fax, 401-722-1720
(*See our ads on pages 3, 253.*)

Technic Inc., Future Automation 5400 Commerce Ave. Moorpark, CA 93021 805-378-0030 fax, 805-532-1344

Technic Inc., Surface Finishing Technologies 12200 34th St., N. Clearwater, FL 34622 727-577-7777 fax, 727-578-7664

Technical Coatings Co. Ltd. 1164 Walkers Line Burlington, Ont. L7M 1V2, Canada 905-335-3561 fax, 905-332-5415

Technicorp 646 Eyster Blvd. Rockledge, FL 32955 407-631-6817 800-541-1971 fax, 407-631-6824

Technology Applications Group Inc. 4957 10th Ave., S. Grand Forks, ND 58201 701-746-1818 fax, 701-746-1910

Technotreat Corp. 6216 S. Lewis Tulsa, OK 74136 918-742-5052 fax, 918-742-5585

TecNu 66 W. Springer Dr., Suite 314 Highlands Ranch, CO 80126-2308 303-471-0999 fax, 303-471-1104

Tek-Temp Inc. 401 Magnolia Ave. Croydon, PA 19021 215-788-5528 fax, 215-788-7737

Teknocom Inc. 1 Circle Dr., Box 149 Potsdam, NY 13676 315-265-1313 800-724-5265 fax, 315-265-*1536*

Teledyne Brown Engineering, Hastings Instruments P.O. Box 1436 Hampton, VA 23661 757-723-6531 800-950-2468 fax, 757-723-3925

Tellkamp Systems Inc. 15523 Carmenita Rd. Santa Fe Springs, CA 90670-5609 562-802-1621 fax, 562-802-1303

Telsonic Ultrasonics 603 Heron Dr. Bridgeport, NJ 08014 609-241-0400 800-691-3111 fax, 609-241-0741

Tepromark International Inc. 206 Mosher Ave. Woodmere, NY 11598 516-569-4533 800-645-2622 fax, 516-295-5991

Terpene Technologies Inc. 1200-A Scottsville Rd., Ste. 130 Rochester, NY 14624 716-235-3860 fax, *716-235-3994*

Terracon 5 Boynton Rd., Hopping Brook Park Holliston, MA 01746-1446 508-429-9950 fax, 508-429-8737

Testerion, Canada Inc. 79 Milliken Blvd., Unit #4 Scarborough, Ont. M1V 1V3, Canada 416-292-0726 fax, 416-292-3254

Tetra Technologies Inc. 25025 I-45 N. The Woodlands, TX 77380 281-364-2990 fax, 281-367-6471

Texo Corp. 2828 Highland Ave. Cincinnati, OH 45212 513-731-3400 800-998-8396 fax, 513-731-8113
(*See our ad on page 122.*)

Therma-Tron-X Inc. 1155 S. Neenah Ave. Sturgeon Bay, WI 54235-1996 920-743-6568 fax, 920-743-5486

Thermco Electric P.O. Box 126 Kenilworth, NJ 07033 908-298-1336 fax, 908-298-1339

Thermionic Products Co. 16 Interhaven Ave. North Plainfield, NJ 07060 908-754-7616 fax, 908-756-8169

Thermo-Cote Inc. 295 Vreeland Ave., P.O. Box 247 Paterson, NJ 07543 973-345-6206 fax, 973-278-7512
(*See our ad on page 225.*)

Thermonic Inc. 1464 Graham-Bell Boucherville, Que. J4B 6H5, Canada 514-641-9555 fax, 514-641-9239

Thermoplastic Valves Inc. 53 S. 7th St. Emmaus, PA 18049 610-967-6388 fax, 610-967-6448

3M Co., Abrasive Systems Div. 3M Center, Bldg. 223-6N-01 St. Paul, MN 55144-1000 651-575-3469 800-742-9546 fax, 800-852-4668

3M Co. 3M Center Bldg. 515-3N-06 St. Paul, MN 55144 651-737-6501 800-364-3577 fax, 651-737-7117

3R Mineral & Mfg. Co. 2400 N. 36th St. Tampa, FL 33605 813-247-5860 fax, 813-247-1266

Tilton Rack & Basket Corp. 66 Passaic Ave. Fairfield, NJ 07004 973-226-6010 fax, 973-227-4155
(*See our ad on page 713.*)

Timesavers Inc. 5270 Hanson Ct. Minneapolis, MN 55429 612-537-3611 800-537-3611 fax, 612-537-9247

Tiodize Co. Inc. 15701 Industry Ln. Huntington Beach, CA 92649 714-898-4377 fax, 714-891-7467

Tipton US Corp. 8411 Seward Rd. Hamilton, OH 45011 513/860-0776 800-344-0776 fax, 513/860-0983
(*See our ad on page 115.*)

Titan International Inc. 205 Chester Ave., Ste. 100 Moorestown, NJ 08057 609-786-1147 800-435-4644 fax, 609-786-3978
(*See our ads on pages 239, 317.*)

Titan Metal Fabricators Inc. 1721 Fiske Pl. Oxnard, CA 93033 805-487-5050 fax, 805-487-5047
(*See our ads on pages 707, 765.*)

Titan Tool Supply Co. P.O. Box 569 Buffalo, NY 14207-0569 716-873-9907 fax, 716-873-9998

Tivian Industries Ltd. P.O. Box 6448 Providence, RI 02940 401-722-5975 fax, 401-722-5977

Tiyoda Mfg. U.S.A. Inc. 1613 Lockness Pl. Torrance, CA 90501 310-539-5471 fax, 310-539-5881

Todco Industries Inc. 210 Campus Dr. Arlington Hts., IL 60004 847-577-2424 fax, 847-577-8374

Tolber Div., Pyramid Plastics Inc. 220 W. 5th St. Hope, AR 71801 870-777-3251 fax, 870-777-8056

Topline Mfg. Co. 1576 E. LaPalma Anaheim, CA 92807 714-777-6865 fax, 714-282-1159

Tosoh SMD Inc. 3600 Gantz Rd. Grove City, OH 43123-1895 614-875-7912 fax, 614-871-9542

Total Filter Technology Inc. P.O. Box 500 Harvard, MA 01451 978-251-1241 fax, 978-251-1241

Tower Chemical Corp. 2703 Freemansburg Ave. Easton, PA 18042 610-253-6206 fax, 610-258-9695

Tracer Products, Div. of Spectronics P.O. Box 10324 Westbury, NY 11590 516-333-1254 800-641-1133 fax, 516-876-8411

Transene Co. Inc. Route One Rowley, MA 01969 508-948-2501 fax, 508-948-2206

Tranter Inc. 1054 Claussen Rd., Ste. 314 Augusta, GA 30907 706-738-7900 fax, 706-738-6619
(*See our ad on page 757.*)

Tranter Inc. P.O. Box 2289 Wichita Falls, TX 76307 940-723-7125 fax, 940-723-5131

Treatment Products Corp. P.O. Box 444 Thorndale, PA 19372-9998 610-384-6279 fax, 610-384-6239
(*See our ad on page 808.*)

Treibacher Schleifmittel Corp. 2000 College Ave. Niagara Falls, NY 14305 716-286-1250 800-394-8872 fax, 716-286-1224

Tri-Mer Corp. 1400 Monroe St., P.O. Box 730 Owosso, MI 48867-9969 517-723-7838 fax, 517-723-7844

Triad Industries Inc. 632 S.W. 2nd Ave. Forest Lake, MN 55025 612-464-1678

Trilectron Industries Inc. 1 Forassetto Way, Unit 1 Lincoln Park, NJ 07035 973-633-1117 fax, 973-633-0006

Trionetics Inc. 2035 Midway Dr. Twinsburg, OH 44087 330-425-2846 fax, 330-425-2908

Triple-S Chemical Products Inc. 3464 Union Pacific Ave. Los Angeles, CA 90023 323-261-7301 800-308-7301 fax, 323-261-5567

TriTech Technologies Inc. 1275 W. Roosevelt Rd., Ste. 104 West Chicago, IL 60185 630-351-3000 888-351-3575 fax, 630-351-3011
(*See our ad on page 639.*)

Tronex Chemical Corp. 48602 Downing St. Wixom, MI 48393 248-449-4075 fax, 248-449-4204

Tru-Chem Co. Inc. P.O. Box 261001 Columbus, OH 43226-1001 614-274-1638 888-878-2436 fax, 614-761-8010

Tru-Plate Process Inc. 70 Industry Dr. West Haven, CT 06516 203-937-0533 800-932-7006 fax, 203-933-8646

Tru-Square Metal Products P.O. Box 585 Auburn, WA 98071 253-833-2310 800-225-1017 fax, 253-833-2349

Trueheat Corp. 700 Grand St. Allegan, MI 49010 616-673-2145 fax, 616-673-7219

Trutec Industries 4795 Upper Valley Pike Urbana, OH 43078 513-653-8500 fax, 513-652-3647

Turbo-Finish Process Laboratories 44 Kearsarge St. Bartlett, NH 03812 603-374-2341 800-723-4554 fax, 603-374-2366
(*See our ad on page 119.*)

Turnkey Solutions Inc. 103 Godwin Ave. Midland Park, NJ 07432-1813 201-848-7676 fax, 201-848-1643

21st Century Environmental Management 25 Graystone St. Warwick, RI 02886 401-738-3261 800-541-8673 fax, 401-738-1073

Tytronics Inc. 25 Wiggins Ave. Bedford, MA 01730 781-275-9660 fax, 781-275-9665

U

U.C.R. Inc. 826 E. Sumner Ave. Indianapolis, IN 46227 317-783-3188 800-382-9783 fax, 317-787-4715
(*See our ad on page 329.*)

UBM Corp. 407 Hope Ave., P.O. Box 618 Roselle, NJ 07203 908-241-8652 fax, 908-241-7288

UF Strainrite 48 Commercial St., P.O. Box 1667 Lewiston, ME 04241 207-777-3100 fax, 207-777-3177

UFS Corp. 330 N. 400 E. Valparaiso, IN 46383-9704 219-464-2027 fax, 219-464-8646

UIC Inc. P.O. Box 863 Joliet, IL 60434 815-727-5431 800-342-5842 fax, 815-744-1561

UVIII Systems Inc. P.O. Box 447 Millis, MA 02054 508-883-4881 fax, 508-376-4748

Ultimate Systems Inc. P.O. Box 11188 Jackson, MS 39283-1188 601-981-3723 fax, 601-981-5906

Ultra-Kool Inc. 500 County Line Rd., P.O. Box 458 Gilbertsville, PA 19525 610-367-2019 fax, 610-367-8396

Ultramatic Equipment Co. 8502 E. Via De Ventura, Ste. 210 Scottsdale, AZ 85258 602-951-6000 fax, 602-951-0448

Ultraseal America Inc. 347 W. State St., P.O. Box 146 Huntington, IN 46750-0146 219-356-2121 fax, 219-356-3131

Ultrasonic Power Corp. 239 E. Stephenson St. Freeport, IL 61032 815-235-6020 800-575-0168 fax, 815-235-6059

Ulvac, North American Corp. 401 Griffin Brook Dr. Methuen, MA 01844 978-686-7550 fax, 978-689-6301

Uni-Spray Nozzles Inc. 44 Durward Pl. Waterloo, Ont. N2L 4E4, Canada 519-885-4270 fax, 519-885-4325

Unified Equipment Systems Inc. 42950 N. Walnut Clinton Twp., MI 48036 810-307-3770 fax, 810-307-3775
(*See our ad on page 617.*)

Union Tool Corp. P.O. Box 935 Warsaw, IN 46581 219-267-3211 fax, 219-267-5703

Unipure Environmental 1440 N. Harbor Blvd., Ste. 125 Fullerton, CA 92835 714-870-1578 800-323-8647 fax, 714-870-4576
(*See our ad on page 807.*)

Unique Industries Inc. Mohawk Ave. Ext., P.O. Box 417 Derby, CT 06418 203-735-8751 fax, 203-736-0906

Unit Liner Co. 7801 N. Kickapoo Shawnee, OK 74801 405-275-4600 800-633-4603 fax, 405-275-4625

Unitech Industrial Inc. 16 South Ave., P.O. Box 330 Wappingers Falls, NY 12590 800-277-5522 fax, 914-297-2919

United Abrasive Inc. 19100 Industrial Dr. Vulcan, MI 49892 906-563-9249 800-228-2925 fax, 906-563-8739

United Air Specialists Inc. 4440 Creek Rd. Cincinnati, OH 45242-2832 513-891-0400 800-992-4422 fax, 513-891-4882

United Refining and Smelting Co. 3700 N. Runge Ave. Franklin Park, IL 60131 847-455-8800 fax, 847-455-3232

U.S. Baird Corp. 1700 Stratford Ave., P.O. Box 9706 Stratford, CT 06615-0887 203-375-3361 fax, 203-378-5197

U.S. Centrifuge 4011 Championship Dr. Indianapolis, IN 46268 317-299-2020 800-899-2040 fax, 317-299-2284

U.S. Chemical & Plastics Inc. 1446 W. Tuscarawas St. Canton, OH 44702 330-455-4311 800-321-0672 fax, 330-455-6169

U.S. Liner Co. 10845 Wornell Rd. Kansas City, MO 64114 816-942-2275 800-811-8055 fax, 816-942-2354
(*See our ad on page 673.*)

U.S. Plastic Corp. 1390 Neubrecht Rd. Lima, OH 45801 419-228-2242 800-537-9724 fax, 419-228-5034

U.S. Specialty Color Corp. 5624 Cannon Dr. Monroe, NC 28110 704-292-1476 fax, 704-292-1675
(*See our ad on page 491.*)

U.S. Technology Corp. 220 7th St. Canton, OH 44702 330-455-1181 fax, 330-455-1191

Unitron Inc. 170 Wilbur Pl. Bohemia, NY 11716 631-589-6666 fax, 631-589-6975

Universal Equipment Mfg. Co. Inc. 3075 S. Gate Ln. Chico, CA 95928 530-342-6023 fax, 530-342-6074

Universal Industrial Equipment Co. 509 Sharptown Rd., P.O. Box 561 Bridgeport, NJ 08014 609-467-5270 fax, 609-467-5511

Universal Rack Co. 70 Athens Dr. Lebanon, TN 37122 615/754-6660 fax, 615/754-6635

Univertical Corp. 203 Weatherhead St. Angola, IN 46703 219-665-1500 fax, 219-665-1400
(*See our ads on pages 239, 277.*)

Uniwest 1021 N. Kellogg St. Kennewick, WA 99336 509-783-0680 fax, 509-735-6872

Upton Industries Inc. 30435 Groesbeck Hwy. Roseville, MI 48066 810-771-1200 fax, 810-771-8970

USFilter Corp. 40-004 Cook St. Palm Desert, CA 92211 760-341-9368 fax, 760-340-0098

USFilter Recovery Services Inc. 2430 Rose Pl. Roseville, MN 55113 651-633-1300 800-732-3226 fax, 651-633-5074

USFilter/Filterite 2118 Greenspring Dr. Timonium, MD 21093 410-252-0800 800-345-8377 fax, 410-560-2857

USFilter/Interlake 2600 S. 17th Ave. Broadview, IL 60153 708-345-7290 fax, 708-345-8006

USFilter/Ionpure 10 Technology Dr. Lowell, MA 01851 978-934-9349 800-466-7873 fax, 978-441-6025

USFilter/IWT 4669 Shepherd Trail, P.O. Box 560 Rockford, IL 61105-0560 815-877-3046 800-333-3458 fax, 815-877-0172

USFilter/JWI 2155 112th Ave. Holland, MI 49424-9604 616-772-9011 800-245-3006 fax, 616-772-4516

USFilter/Memtek 28 Cook St. Billerica, MA 01821 978-262-2300 800-527-0433 fax, 978-667-1731

USFilter/Permutit 30 Technology Dr. Warren, NJ 07059 908-668-1700 fax, 908-668-1393

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USFilter/VL Rampe 1601 Brooks Dr., P.O. Box 529 Marshall, MI 49068 616-789-0786 fax, 616-789-0720

USFilter/Warrendale 181 Thorn Hill Rd. Warrendale, PA 15086 724-772-0044 800-525-0658 fax, 724-772-1360
(*See our ad on page 823.*)

USFilter/Wheelabrator 1605 Executive Dr. LaGrange, GA 30240 706-884-6884 800-544-4144 fax, 706-884-0568

Uyemura International Corp. 2625 E. Cedar St. Ontario, CA 91761 909-923-2294 800-486-4842 fax, 909-923-7643
(*See our ad on page 255.*)

V

VSM Abrasives Corp. 1012 E. Wabash St. O'Fallon, MO 63366-2774 314-272-7432 800-737-0176 fax, 314-272-6394

Vacuum Engineering & Materials Co. Inc. P.O. Box 4480 Santa Clara, CA 95056-4480 408-986-8900 fax, 408-986-8980

Vacuum Inc. 5541 Central Ave. Boulder, CO 80301 303-444-8750 fax, 303-444-0104

Vacuum Plating Technology Corp. 254 Kinney Dr. San Jose, CA 95112 408-998-8998 fax, 408-998-4795

Vacuum Research Corp. 2419 Smallman St. Pittsburgh, PA 15222 412-261-7630 800-426-9340 fax, 412-261-7220

Van Air Systems Inc. 2950 Mechanic St. Lake City, PA 16423 814-774-2631 800-840-9906 fax, 814-774-0778

Van Industries Inc. 1285 Wordsworth Ferndale, MI 48220 248-398-6990 fax, 248-398-8306

Vanaire Ltd. 10151 Bunsen Way Louisville, KY 40299 502-491-3553 fax, 502-491-5182

Vanton Pump & Equipment Corp. 201 Sweetland Ave. Hillside, NJ 07205-1793 908-688-4216 fax, 908-686-9314

Vapor Blast Mfg. Co. 3025 W. Atkinson Ave. Milwaukee, WI 53209 414-871-6500 fax, 414-871-7683

Vapor Engineering Inc. P.O. Box 15209 Pensacola, FL 32514 850-434-3191 fax, 850-478-0369

Vapor Technologies Inc. 6400 Dry Creek Pkwy., P.O. Box 11170 Boulder, CO 80301 303-652-8500 fax, 303-652-8600

Varian Associates Inc., Vacuum Products Div. 121 Hartwell Ave. Lexington, MA 02173-3133 781-861-7200 800-882-7426 fax, 781-860-5437

Veeco Industrial Measurement 105 Comac St. Ronkonkoma, NY 11779 631-738-9300 800-248-3326 fax, 631-738-9329
(*See our ad on page 575.*)

VerdEco Technologies Ltd. 7/B New Industrial Park, P.O. Box 258 Yoqneam, 20692 Israel 972 4 959 9520 fax, 972 4 959 0722

Vergason Technology Inc. 88 State Route 224 Van Etten, NY 14889 607-589-4429 fax, 607-589-6955

Versa-Matic Pump Co. 6017 Enterprise Dr. Export, PA 15632-8969 724-327-7867 800-843-8210 fax, 724-327-4300

Viatec/Hastings Engineered Systems 2000 Logston Blvd. Richland, WA 99352 509-375-3268 fax, 509-375-3017

Vibra Chem Co. Inc. 656 Michael Wylie Dr. Charlotte, NC 28217 704-523-2123 fax, 704-523-6957

Vibra Finish Co. 8491 Seward Rd. Hamilton, OH 45011 513-870-6300 800-253-1941 fax, 513-870-6336
(*See our ad on page 115.*)

Vibra Finish Ltd. 5329 Maingate Dr. Mississauga, Ont. L4W 1G6, Canada 905-625-9955 fax, 905-625-5261

Victory White Metal Co. 6100 Roland Ave. Cleveland, OH 44127 216-271-1400 800-635-5050 fax, 216-271-6430

Viking Corp. 3810 N. Toben Wichita, KS 67226 316-634-6699 800-835-1096 fax, 316-634-6658

Vincent Metals Corp. 84 Canonchet Rd. Hope Valley, RI 02832 401-539-3053 fax, 401-539-0544
(*See our ad on page 250.*)

Viron International 505 Hintz Rd. Owosso, MI 48867-9603 517-723-8255 fax, 517-723-8417
(*See our ad on page 785.*)

Vulcanium Anodizing Systems, Div. of Industrial Titanium Corp. 3045 Commercial Ave. Northbrook, IL 60062-1997 847-498-3111 888-922-0052 fax, 847-498-3392
(*See our ad on page 481.*)

Vulcanium Plating Systems, Div. of Industrial Titanium Corp. 3045 Commercial Ave. Northbrook, IL 60062-1997 847-498-3111 888-922-0040 fax, 847-498-3392
(*See our ad on page 761.*)

Vulkan Blast Shot Technology 10 Plant Farm Rd., Unit 2, P.O. Box 2052 Brantford, Ont. N3T 5W5, Canada 519-753-2226 800-263-7674 fax, 519-759-8472

W

W.E.S. Inc. 6389 Tower Ln. Sarasota, FL 34240 941-371-7617 fax, 941-378-5218

W.R. Associates Inc. 2210 Encinitas Blvd., Ste. W Encinitas, CA 92024 760-436-9194 800-348-3287 fax, 760-436-9321

WIT Sales & Refining 538 Phelan Ave. San Jose, CA 95112 408-295-6414 fax, 408-295-1464

WMX Technologies 3003 Butterfield Rd. Oak Brook, IL 60521 630-572-8800 fax, 630-572-3094

WSI Chemical Inc. 1808 N. National Ave. Springfield, MO 65803 417-865-2862 fax, 417-865-6978

Walchem Corp. 5 Boynton Rd., Hopping Brook Pk. Holliston, MA 01746-1446 508-429-1110 fax, 508-429-7433
(*See our ad on page 433.*)

Walgren Co. 3677 Sysco Ct., S.E. Grand Rapids, MI 49512 616-942-8910 800-831-5555 fax, 616-942-8915
(*See our ad on page 623.*)

Wallace & Tiernan 25 Main St. Belleville, NJ 07109 973-759-8000 fax, 973-759-8775

Walrus Pump & Filtration LLC 709 N. Dallas St. Amarillo, TX 79017 806-383-3355 fax, 806-838-5577
(*See our ad on page 743.*)

Walther Corp. 694 Wilburn, Hwy. 110 E., P.O. Drawer 1079 Heber Springs, Ar 72543 501-362-8175 fax, 501-362-9484

Warren Rupp Inc., A Unit of Idex Corp. 800 N. Main St., P.O. Box 1586 Mansfield, OH 44901-1568 419-524-8388 fax, 419-522-7867

Warrender Ltd. 27845 N. Irma Lee Cir. Lake Forest, IL 60045 847-247-8677 888-247-8677 fax, 847-247-8680

Washington Mills Ceramics Corp. P.O. Box 112 Lake Wales, FL 33853-0114 888-676-1846 fax, 941-676-1985

Washington Mills Electro Minerals Corp. 1801 Buffalo Ave., P.O. Box 423 Niagara Falls, NY 14302 716-278-6600 800-828-1666 fax, 716-278-6650
(*See our ad on page 99.*)

Wasserman, Arthur 35 E. 35th St., P.O. Box 6 New York, NY 10016 212-679-8005

Waste Treatment Equipment Specialties Co P.O. Box 44096 Cleveland, OH 44144 440-808-8844 fax, 440-808-8850

Wastesaver Technologies 80 Townline Rd. Plainville, CT 06062 860-793-8660 fax, 860-793-8668

Wastewater Treatment Systems 1235 Elko Sunnyvale, CA 94089 408-541-8600 fax, 408-541-8615

Water and Wastewater Equipment Co., Div. of Phil-Mar Equipment Inc. 1466 E. 357th St. Eastlake, OH 44095 440-942-7070 fax, 440-942-3622
(*See our ad on page 801.*)

Water Systems Inc. 910 Commonwealth Ave. Newton, MA 02159 617-332-1696 fax, 617-965-7704

Water Technology 564 Industrial Way, E. Macon, GA 31201 912-743-3050 fax, 912-742-3555

Water Treatment Technologies Inc. 221 E. Main St. Milford, MA 01757-2825 508-473-6800 fax, 508-473-4030

Water Works, A Div. of Polydisc P.O. Box 122 Crown Point, IN 46307 219-663-8210 800-232-9334 fax, 219-662-1503

Waterlink/Lanco Environmental Products 4315 Three Mile Rd., N.W. Grand Rapids, MI 49544 616-791-9100 800-965-3922 fax, 616-453-1832
(*See our ads on pages 805, 807.*)

Watlow Electric Mfg. Co. 12001 Lackland Rd. St. Louis, MO 63146 314-878-4600 fax, 314-878-6814

Watropur Corp. 1931 Industrial Dr. Libertyville, IL 60048 847-367-5150 fax, 847-367-1787

Wayne Products Inc. P.O. Box 788 Frazer, PA 19355 610-251-0933 800-255-5665 fax, 610-251-0218

Wear-Cote International Inc. 101 Tenth St., P.O. Box 4177 Rock Island, IL 61204-4177 309-793-1250 fax, 309-786-6558
(*See our ad on page 429.*)

Webster Pumps 999 Chenault Rd. Frankfort, KY 40601 502-695-1300 800-766-1950 fax, 502-695-4059
(*See our ad on page 739.*)

Weiler Corp. 1 Wildwood Dr. Cresco, PA 18326-0149 717-595-7495 888-600-5857 fax, 717-595-2002

Weiner, Milton 28121 Ridgethorne Ct. Ranchos Palos Verdes, CA 90275-3253 310-544-0470

Wellman Thermal Systems Corp. 1 Progress Rd. Shelbyville, IN 46176 317-398-4411 fax, 317-392-5275

West Coast Rack & Mfg. Inc. 5730 Paloma Ave. Los Angeles, CA 90011 323-234-0604 fax, 323-234-2675
(*See our ad on page 713.*)

Westar Mfg. Corp. 814 E. First Ave., P.O. Box 109 Dorchester, WI 54425 715-654-5000 fax, 715-654-5566

Westbrook LLC 5063 Ore Bank Rd. York, PA 17406 717-757-3354 888-564-5556 fax, 717-840-0982

Western Reserve Mfg. Co. Inc. 5311 W. River Rd., N. Lorain, OH 44055-3799 216-277-1226 fax, 216-277-9526

Western Sonics 20468 Carrey Rd. Walnut, CA 91789 909-468-0600 fax, 909-468-0606

Westport Environmental Systems 251 Forge Rd. Westport, MA 02790-0217 508-636-8811 800-343-9411 fax, 508-636-2088

Wheel Doctor 6969 Oakland Chase Memphis, TN 38125 901-756-1142 fax, 901-757-9246

Wheelabrator Abrasives Inc. 1 Abrasive Ave., P.O. Box 804 Bedford, VA 24523 540-586-0856 800-358-7468 fax, 540-586-6286

White Laboratory & Co., J. 6635 Florence Ave., Unit 323 Bell Gardens, CA 90201 562-927-4427

White Technologies Inc., S.S. 151 Old New Brunswick Rd. Piscataway, NJ 08854 732-752-8300 800-779-4483 fax, 732-752-3750

Whitford Corp. P.O. Box 2347 West Chester, PA 19380 610-296-3200 fax, 610-647-4849

Whyco Technologies Inc. 670 Waterbury Rd. Thomaston, CT 06787-2099 860-283-5826 fax, 860-283-6153
(*See our ad on page 341.*)

Wilden Pump & Engineering Co. 22069 Van Buren St. Grand Terrace, CA 92313-5651 909-422-1730 fax, 909-783-3440
(*See our ad on page 737.*)

Wilkens-Anderson Co. 4525 W. Division St. Chicago, IL 60651 773-384-4433 fax, 773-384-6260

Williams Advanced Materials 2978 Main St. Buffalo, NY 14214 716-837-1000 fax, 716-833-2926

Williamsville Buff Co. 200 Seward Ave. Utica, NY 13503 315-735-9252 fax, 315-797-0058

Willson Safety Products, Div. of WGM Safety Corp. 2nd and Washington Sts., P.O. Box 622 Reading, PA 19603-0622 610-376-6161 fax, 610-371-7725

Wilson Instruments Div., Instron Corp. 100 Royall St. Canton, MA 02021 781-575-6000 800-695-4273 fax, 781-575-5770

Wipe-Tex International Corp. 1200 Zerega Ave. Bronx, NY 10462 800-643-9607 fax, 718-597-9438

Wisconsin Porcelain Co. 120 Lincoln St. Sun Prairie, WI 53590 608-837-5155 fax, 608-837-0808
(*See our ad on page 113.*)

Witt Associates Ltd., F.C. 2211 E.L. Andersen, N., P.O. Box 488 Claremore, OK 74018 918-342-0083 800-323-3335 fax, 918-342-3932

Working Solutions Inc. 4810 Nett St. Houston, TX 77007 713-862-3868 800-829-4419 fax, 713-862-5591

World Resources Co. 170 Walnut Ln. Pottsville, PA 17901-8559 717-622-4747 800-296-4747 fax, 717-622-7369

Wyko Corp. 2650 E. Elvira Rd. Tucson, AZ 85706 520-741-1044 800-366-9956 fax, 520-294-1799

Y

Yamada America Inc. 1200 Nuclear Dr. W. Chicago, IL 60185 630-231-4083 800-990-7867 fax, 630-231-7398

Yamamoto-Metkishikenki Co. Ltd. 5-28-1 Sendagaya Shibuya-ku Tokyo Japan 81 3352 2475 fax, 81 3 3500 0775

Yerges Mfg. Co. 423 Knapp St. Fremont, OH 43420 419-332-9905 800-332-3058 fax, 419-332-9377
(*See our ad on page 51.*)

Z

Zalcon Inc. 2981 Independence Rd. Cleveland, OH 44115 216-271-1715 800-356-7327

Zarsky Industries 2121 Brittmoore Houston, TX 77043 713-462-1400 800-473-9178 fax, 713-462-3366

Zeiss Inc., Carl One Zeiss Dr. Thornwood, NY 10594 914-747-1800 fax, 914-681-7445

Zeks Air Drier Corp. 1302 Goshen Pkwy., P.O. Box 2660 West Chester, PA 19380 610-692-9100 800-888-2323 fax, 610-692-9192

Zenith Ultrasonics Inc. 85 Oak St. Norwood, NJ 07648-0412 201-767-1332 800-432-7664 fax, 201-768-6999

Zero Discharge Technologies Inc. 165 Front St., Bldg. A/5th Fl. Chicopee, MA 01013 413-592-4242 fax, 413-592-4004

Zinex Corp. 1621 Pacific Ave., Unit # 121 Oxnard, CA 93033 805-486-6994 fax, 805-486-7334
(*See our ads on pages 237, 697.*)

Zophar Mills Inc. 100 26th St. Brooklyn, NY 11232 718-768-0907 fax, 718-768-0910

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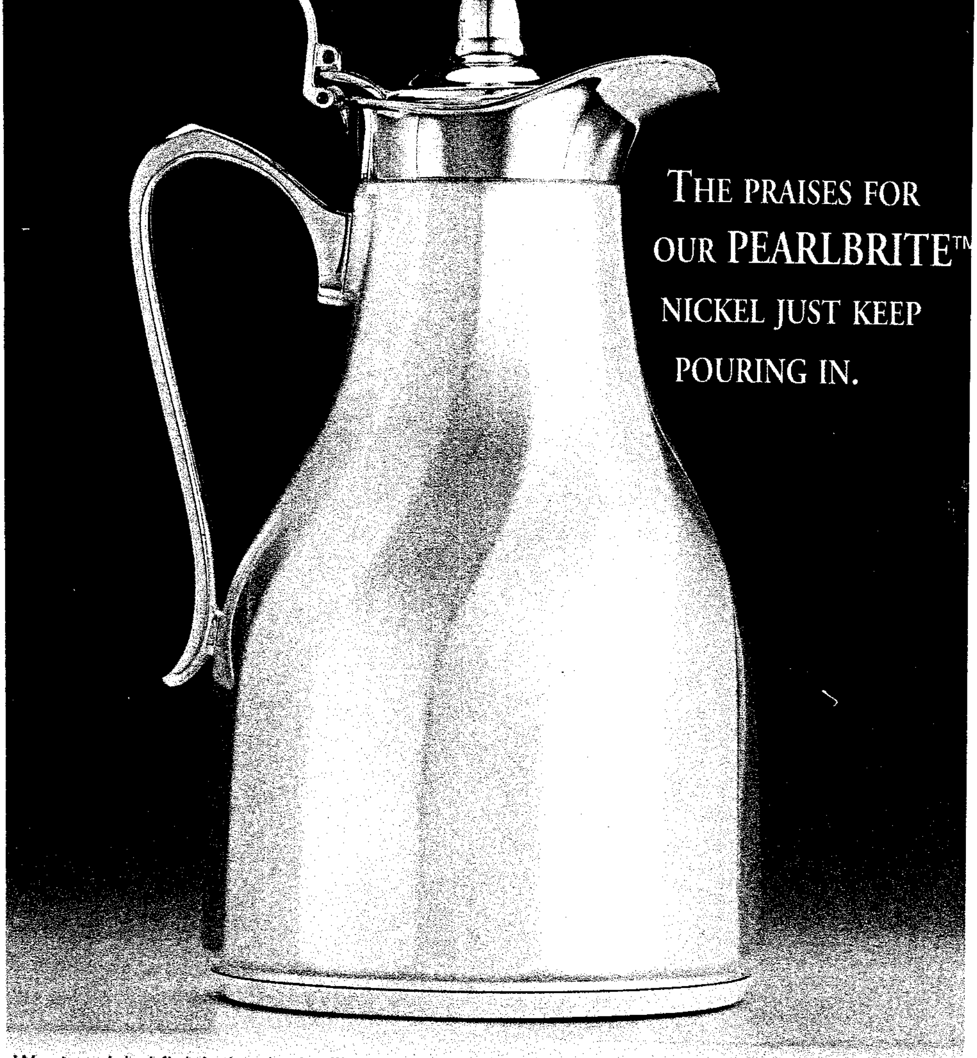
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