Reducing the use of chlorinated solvents for cleaning during metal component production demands a whole new approach. The use of water based cleaning is attractive provided reservations about corrosion, drying and disposal can be overcome. Using specifically designed systems water based cleaning products exhibit extremely effective results especially for particulate soil removal.

Ultrasonic agitation in an aqueous based cleaning solution enhances the effective properties. Dissolved additives provide wetting, dispersion, corrosion inhibition and many other attributes. Water functions as a solvent for the additives and as a carrier for transporting soil. Drying may be obtained by hot air or by dewatering in a light oil. Soil separation systems ensure clean solutions for reuse and eventual disposal as waste. Alternatively ultra high pressure water jets can also provide effective cleaning where the cost is justified by the result obtained.

Practical experience of water based cleaning can be illustrated by reference to three case histories. These include an integrated water based cleaning system using light oil dewatering, which has proved to be successful for more than two years at a major bearing manufacturer.
1. **WATER AS ALTERNATIVE SOLVENT AND CARRIER**

Most cleaning operations are performed using water as a solvent for the cleaning product and as a carrier for the soil. Historically, metal cleaning has employed vapour degreasing and chlorinated solvent dip methods, which are more effective and reduce the risk of corrosion known to be associated with aqueous based cleaning. Aqueous cleaning has sometimes appeared as the inexpensive but inferior alternative to solvent. Certainly aqueous cleaning can be inexpensive but the result obtained is far from inferior.

Water based cleaning techniques require a fundamentally different approach from those used in traditional chlorinated solvent systems. Consequently prospective users must define the needs of the system and adopt appropriate charges accordingly. A willingness to examine new cleaning techniques will result in good cleaning performance, reduced costs and greater environmental benefits.

1.1 Soil Carrier

The main role of water is to act as a carrier transporting soil from the component surface to the soil separation system. Oil on the component surface is displaced, emulsified carried as an emulsion to the oil separator, separated, oil collected and cleaning solution carried back to the component ready for another cycle. Although the mechanism is different there is a clear analogy with the evaporation, condensation, dissolution and drainage cycle of vapour degreasing.

1.2 Solvent

Water alone is not a solvent for the soils found in production cleaning, which are typically oils and metal particles. However it is a solvent for added ingredients which perform the cleaning task. Water based cleaning usually implies a solution of more than 95% water, the remainder being a blend of surfactants, dispersants, corrosion inhibitors and many other additives.

2 **PRODUCTION CLEANING**

The cleaning systems discussed here are considered to be production cleaning techniques. Typically these are employed to remove oil and swarf from components after machining and prior to assembly. It is widely appreciated that premature failure of assembled parts relates directly to the amount and nature of soil present on the component after ineffectual cleaning.

2.1 Soils

Soils can be subdivided into liquid and solid. The liquid component is often oil containing oil soluble additives and derives from the metal working fluid. The solid component is predominantly metal particles from the forming process. The metal particles are normally coated with forming fluid and are not wetted by water.
2.2 System Types

The cleaning system introduces the fluid to the soiled surface, provides some mechanical energy and transports the used solution to the soil separation system. While there are many apparent variations it is convenient to classify water based systems in terms of the way in which they add mechanical energy to the cleaning fluid.

The main variants are:

- spray - low pressure
- spray - high pressure
- immersion - component agitation
- immersion - recirculation
- immersion - ultrasonic

It is common to find two or more types combined in the total cleaning package.

3 SPRAY, ULTRASONIC, DIP IN SEQUENCE (SUDS)

The combination of low pressure spray, ultrasonically and mechanically agitated immersion is becoming as cleaning system designers appreciate the benefits of each type of action. Ultrasonically agitated immersion provides the key stage for particulate soil removal. A pre-wash by low pressure spray can partly remove oily or greasy soil present as a matrix around particles and remove larger particles. A pre-wash can also give time for surfactant penetration into oily soil.

3.1 Cleaning Solution Features

The cleaning fluid must be ultrasonic compatible; this means the cleaning solution must wet both the ultrasonic transducer and the soiled surface. Poor wetting at either surface leaves gas at the interface which because of its ready compressibility will not transmit the mechanical energy of the ultrasonic vibration. The high frequency of vibration used in ultrasonic agitation emphasises the importance of dynamic wetting by the cleaning solution of the component and transducer surfaces.

The solution must be capable of suspending soil particles when removed from the surface, so they may be transported within the wash solution to a filter. In addition to wetting the particle it is helpful if an electrostatic charge can be induced to minimise repulsion or flocculation.

The oily soil component is removed by a combination of mechanical action and displacement by the cleaning solution. Once remove the oil is held as an emulsion for transport to an oil separator. This emulsion must be stable enough to allow transportation but not so stable as to prevent oil removal by the simple static separator. It may be desirable to incorporate a slow demulsifier to aid oil separation, reducing oil build up in solution and hence minimising redeposition.

The foam produced by the wash solution must be minimal otherwise it will steadily increase from the spray bars until reservoir overflow or pump cavitation occurs.

Corrosion preventive components are incorporated into the solution to ensure the component is free from corrosion both during contact with the solution and also for a period after drying. The corrosion preventive action is achieved by a thin adsorbed film, physisorbed or chemisorbed on to the surface. This gives rise to a passivated layer which subsequently reduces the corrosion rate.
Detailed formulation is necessarily complex to meet all the above mentioned criteria, as well as produce a physically stable concentrate of pleasant appearance and ensure prudent use of expensive materials. The outline planning of the cleaning concentrate formulation starts with consideration of the critical parameters, pH, alkaline buffering capacity, foam and cloud point. It is usual to prepare alkaline cleaning solutions as increasing pH improves cleaning, reduces ferrous metal corrosion and improves biostability. Set against the benefits of increasing pH are the problems of light alloy corrosion and, most importantly, safety. Since the cleaning solution is supplied as a liquid concentrate to the end user for dilution to about 1-4% in water it is desirable that the cleaner is strongly buffered. Suitable alkaline buffers should ideally contribute to the detergent building i.e. contributing to water softening, solid particle dispersion and prevent the redeposition of dissolved solids. The classic detergent builder containing polyphosphate is seldom used because of eutrophication concerns. Alternative blends include citrate, carbonate and amineophosphonate. Soluble silicates while effective and inexpensive, restrict the pH to a minimum of 10.5 if separation of insoluble silica gel is to be avoided.

Although intrinsically low foaming nonionic surfactants are used careful control of their solubility is necessary to optimise the benefits of wetting and emulsification against the problem of foam. Nonionic surfactants of this type decrease in solubility with increasing temperature showing a very sharp decrease at a characteristic temperature known as the cloud point. The concentrate must have a cloud point above its storage temperature whilst the dilute solution needs a cloud point below working temperature. A concentrate cloud point of 45 °C (113°F), and a solution cloud point of 20 °C (68°F) would be near ideal but also very difficult to obtain, so a compromise with the temperatures closer together, both about 40 °C (104°F), is not uncommon. The solubility of the surfactant is affected by electrolyte and particularly by hydrotropes, materials which markedly increase the solubility and hence increase the cloud point. Many types of molecules function as hydrotropes usually acting by altering the equilibrium between surfactant available in dissolved aggregates i.e. micelles and surfactant present as undissolved solid.

Using the surfactant above its cloud point ensures a low concentration is available in solution for cleaning, with a reservoir of surfactant circulating as finely divided solid redissolving if the system is allowed to stand and cool.

Combined spray and ultrasonic dip in sequence systems are comparatively forgiving in terms of foam tolerance, which offers the formulator more scope to permit higher concentration of free surfactant.

The influence of water and soil on the foam generated needs to be considered. Calcium and magnesium salts in water generally depress foam by forming slightly soluble salts with fatty acids often present in soils. Soils may contribute species which act as hydrotropes and hence by increasing the surfactant solubility also increase foam.

Having discussed some of the major cleaning features the corrosion inhibition needs to be considered. Typical ferrous metal inhibitors are alkyl carboxylates usually synthetic rather than natural fat derived and often containing multiple carboxylate groups. Since surfactants and dispersants also act by adsorption onto metal surfaces, there is a considerable interference between these components which is often resolved by laborious testing of many minor variations.
Finally the chemical, physical and biological stability of both concentrate and dilute solution must be considered. The chemical stability of the concentrate is largely ensured by close monitoring of the component chemistry. Some physical instability is integral to the product formulation to accommodate the inverse temperature solubility effects previously discussed. Unexpected phase separation can still occur even after apparently thorough checking. While every effort is made to choose base components which are biostable in working conditions it is usual to add a package of biocides.

3.2 System Features

Depending upon the size, weight and number of components to be cleaned a decision on mechanical handling must be made. It is increasingly common for components to be handled individually or in jig held groups. Individual handling provides better presentation to ultrasonic vibration and minimises the risk of inter component damage. Where the component is presented to the cleaning solution by immersion it is important that oily soil is not allowed to separate and collect on the surface. Removing a component through a surface oil layer invites redeposition of the oil. Since the cleaning solution should not form stable fine emulsions with oil it is necessary to provide gentle agitation to keep the oil emulsified; usually the mechanical handling of the system provides sufficient agitation. Using well designed cleaning products static or gravity separation will provide sufficient oil separation to keep oil levels in solution to an acceptable low amount. The static separator will often be in a by-pass loop to give sufficient dwell time. Gravity separation is rarely sufficient for particulate soil although where centrifuges are used to accelerate the separation good results can be obtained. Through flow filters can be used to achieve particulate soil removal down to almost any degree desired limited by costs. Cross flow membrane filters are finding increasing use to give thorough oil removal and depending upon the membrane type can remove water soluble large molecules by ultrafiltration.

Membrane filtration finds its main use in splitting the waste cleaning solution into displaceable water and a pumpable soil concentrate. Membrane filters are sensitive to the composition of the cleaning solution and may become blocked rather easily if a cleaning solution component precipitates on the membrane. Some mechanism for cleaning or renewing filters is required and often scrapers, cross wash or reverse flush are provided.

Cleaning solutions are usually run at temperatures above ambient and ideally above the cloud point or low foam threshold. Cleaning performance generally improves as temperature rises and may increase dramatically if a difficult soil such as a grease is raised above its' melting point. It is worth considering each case on its' merits and the energy cost of higher temperatures may be recouped by lower chemical and drying costs. The whole cleaning process normally takes a number of consecutive stages and the simplest carbination of wash and dry is rarely the optimum. At the very least, including a rinse improves cleaning decreases chemical usage. Often adding pre-wash, multiple rinse, dewatering and air blow off drying have improved performance.

3.3 Case Histories

3.3.1 Bearing Rings, Integrated Ball Bearing Production

After machining and heat treatment bearing rings are finish ground to final dimension before checking and assembly. Prior to assembly it is vital to achieve high standard of cleanliness, especially of particulate soil. The soil present is a mixture of the grinding debris, mainly steel but some abrasive particles, and grinding lubricant which is a neat oil containing some extreme pressure additives.
Replacing chlorinated solvent cleaning for this task requires a specialised system containing the following steps:

**prevash** - low pressure spray of water solution taken from washer bath at 3% 50°C (122°F).

**main wash** - immersion in ultrasonically agitated dip bath, average energy 5W/l, (about 20W/US gal) same solution conditions as prewash.

**rinse** - low pressure spray using freshly filtered wash solution, filter about two microns nominal, same solution conditions as pre wash.

**drain** - a short, 20s transfer allowing some of the wash solution to drain.

**dewater** - immersion in dewatering fluid which displaces water with a light oil film.

**air blow** - removal of excess dewatering fluid

The complete wash and dewatering system is contained in one unit with bearing rings passing through continuously on a conveyor. The wash solution is contained centrally in a 12000 litre (3000 US gal) reservoir feeding a number of individual washers. Individual wash baths are replaced at a turn over rate of about 10-12 times per hour. The central reservoir contains an oil separator on a by-pass loop. As a result of the low volatility of the dewatering fluid, bearing rings exit the washer wet with dewatering oil which provides corrosion protection and lubricity for assembly.

The washing system was proposed and investigated on a laboratory scale in 1988, a prototype designed, constructed and tested during 1989 and factory use began at the end of 1989. Washers run continuously except for reservoir changes or other production changeovers.

Results are subject to variation but some typical results were obtained during prototype testing:

<table>
<thead>
<tr>
<th>Dirt (mg/ring)</th>
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<tbody>
<tr>
<td>before cleaning</td>
</tr>
<tr>
<td>after pre-wash</td>
</tr>
<tr>
<td>after rinse</td>
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<tr>
<td>after dewatering</td>
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These results refer to inorganic, particulate residues and were obtained by solvent washing, filtration and ashing. It was believed that the increase of soil after dewatering was debris from the conveyor and was subsequently reduced after the conveyor running in period, and also as a result of better filtration of the dewatering fluid.

A number of problems have arisen both during the prototype trials and during use in routine production. The most severe difficulty during trials was a severe odour developed by the dewatering fluid. This was partly as a result of poor communication between engineers and chemists which led to the use of copper tubing in the circulation plumbing, which accelerated oxidation of the dewatering fluid after prolonged use. A combination of more stable components for the dewatering fluid, use of chemical stabilisers and change in materials of construction resolved the problem.
During early production use oil build up in the wash solution was rapid and to a higher level than anticipated, with 1% being reached on occasion. This was a result of the wash solution being agitated more than originally anticipated due to a temporary small capacity central reservoir being used which gave rapid wash solution turnover.

A combination of a retuning of the wash solution and a six fold increase in central reservoir capacity resolved the difficulty. The solution rebalancing involved a modification to its emulsifying characteristics by a change of the surfactant system.

Unexpected difficulties still arise and recently a particularly interesting problem emerged because of improved on-line monitoring of cleanliness in which the results obtained appeared to change rapidly and unpredictably. Initially this was thought to be due to changes in dewatering performance permitting residual wash solution to remain on the rings. While it was relatively simple to improve dewatering performance, there was a trade off with water build up in the dewatering fluid as moved wash solution did not demulsify completely; this led to unacceptably short product life. Empirical trials showed that the different approach of a small increase in wash solution concentration greatly improved the results. While this reflects a small boost in cleaning performance it became apparent that the major effect was an improvement in dewatering performance. This is thought to be as a result of surfactant carry over from the cleaning solution to the dewatering bath.

Further improvement in the total system is being considered such as recycling dewatered wash solution back to the wash solution reservoir.

The total package is not cheap to install and is rather inflexible in application but is extremely productive, inexpensive to run, provides good results and achieves the improved environmental objectives.

3.3.2 Hydraulic Brake Cylinders- Automobile Braking Systems

Finish cleaning of hydraulic brake cylinders involves the removal of grinding lubricant and grinding debris. Detailed examination showed that the soil was predominantly metal particles with the presence of inorganic elements specifically calcium and silicon, from unknown origin. The majority of components are steel with a small percentage being aluminium alloys, which have previously been anodised or passivated.

The sequence chosen is:

first wash - intensive flood washer which combines immersion, high pressure solution injection into the main wash bath and a rotating component basket to ensure all components are exposed to the underwater jetting. Solution is at 2%, 70°C (158°F).

second wash - ultrasonically agitated dip, 2%, 70°C (158°F).

first rinse - dip in 0.5% solution.

second rinse - dip in 0.5% solution.

dry - hot air blow.

The washer has provision for an oil removal cascade such that the separated oil from the second rinse is passed back to the first rinse and so on back to the first wash.
The system was commissioned in mid 1991 and immediately had foam problems due to the high mechanical agitation of the first wash. Since foam entrainment reduces the effectiveness of the jet injection and hence reduces cleaning performance a complete change to a lower foaming cleaning solution was necessary. Since the wash temperature is rather high a cleaning solution with a cloud point of about 55°C (131°F) has proven satisfactory. Many of the other commissioning problems which included poor oil separator operation and poor drying proved to be linked to the foam problem and solving that cured most other difficulties.

In use the system has comfortably exceeded the targets specified both in terms of total soil (at less than 8mg per cylinder) and in terms of particle size distribution.

Because of greater complexity this is a rather expensive system to install but has proven robust and effective in its first year of use. The batch wise component handling limits throughput but the washer has ample capacity for current rates and the flexibility to be upgraded or retasked. The customer appears to be convinced as they have installed other similar wash systems both for the same purpose and for other cleaning tasks.

4 ULTRA HIGH PRESSURE CLEANING

Ultra high pressure (UHP) cleaning poses quite different challenges to the cleaning - product formulator from any other type of production cleaning system. Essentially all the cleaning of particulate soil is obtained by the mechanical action of the high pressure jet with the cleaning solution providing dispersion, stabilisation and corrosion protection. Depending on the pressure, volume and entrained abrasive content water jets can achieve many effects ranging from loose debris removal from hard surfaces through to removal of epoxy paint, millscale and casting cores. Production cleaning is generally at the mid end of the water jet energy spectrum and typically uses pressures of 150 - 700 bar (2000-10000 psi), volumes of 100 - 400 l/min (25-100 US gall/min) and no added abrasive. The system designer will aim to achieve the desired result at a minimum pressure and flow rate. These parameters are established on a variable rig, cleaning actual components.

With such large pressures the solution is subject to extremely high agitation with the consequent risk of foam and air entrainment. A degree of air entrainment is inevitable even with water when the volume of liquid may increase by 100% with the washer in continuous recirculation.

UHP washers are expensive, typically an order of magnitude higher than ultrasonic dip washers, but can more easily handle large components and remove difficult soils.

4.1 Cleaning Solution Features

The first and over-riding priority is to avoid foam. Conventional cleaning surfactants, even those of claimed low foam characteristics are unsuitable. All additives have to be considered in terms of their liability to foam, including those not normally considered as foam producing. The next priority is corrosion protection both of the cleaned component and of the washer. The working solution can contribute to cleaning performance by ensuring that the soil removed is held in suspension and transported to the filtration and separation system, rather than being removed by the high pressure jet only to be redeposited as soon as the jet moves on.
We electrolytes such as polyphosphate can contribute to both the anti-redeposition and anti-corrosion features of the product although unfortunately waste water problems largely preclude their use. Alternatives such as hydroxycarboxylates and arminophosphonates show degrees of both anti redeposition and anti corrosion. While particulate soil dispersion can be aided by adsorbed electrolytes increasing the surface electrostatic charge it is more difficult to achieve consistent effects on oily soil. In principle it should be possible to control the oil/water interface without affecting the air/water interface and hence creating foam problems. This control is probably best approached by ion adsorption although this has to be quite specific since general increases in solution ionic strength should be minimised to control corrosion.

Minor issues such as biological stability also have to be addressed since the typical running temperature of 35-45 C (95-113°F) is conducive to micro biological growth and long life is a design objective.

4.2 System Features

The recirculation typically uses a machine reservoir to feed a high pressure pump which feeds a limited number of jets. Either the jets or the component moves such that all the surface is exposed to the high pressure jet. The solution drains to a collection area, is filtered, oil separated and cooled prior to return to the main reservoir. Cooling is necessary to maintain solution temperatures reasonably low after the heat input of the pump. Presentation of the component is invariably mechanised for safety reasons.

4.3 Case history-Gmtshaft Clean, Automobile Engine Production

In 1986 a low volume, prestige car, manufacturer decided to employ UHP washing for finish cleaning of camshafts. A camshaft poses rather similar problems to those previously described in that the main soils are grinding lubricant and metal particles. The difference lies in the geometry with complex internal oilways posing problems. Ultrasonic agitation is masked and low pressure sprays will not reach the internal areas. The high pressure jet can be directed to flush through the internal areas and although pressures will usually drop rapidly away from the nozzle the very fact of the confined space becomes of advantage in transmitting the energy of the jet.

At the design stage it became apparent that corrosion protection was very important both to the washer manufacturer and the customer. The washer manufacturer, Reiss-Elan had problems with an earlier generation of cleaning product which in extreme cases had led to a pump life of only three to four months between overhauls. Similarly protection of the camshaft after washing was very important in a low volume factory where components may be stored without further protection.

Initially an unusually high concentration of inhibitors with a minimum of other components which might interfere with protection was used. In clean washers in frequent use this was satisfactory but in circumstances where the washer was used intermittently bacterial and fungal growth occurred. As a result a low level of biocide was incorporated into the cleaning solution with a slight deterioration in corrosion protection.

Generally the wash system has worked well and the user has since installed a number of similar UHP washers for finish cleaning of cylinder heads, inlet manifolds and similar complex form components.
SOLUTION RECYCLING AND DISPOSAL

After doubts about corrosion and drying the most common query about water based cleaning concerns disposal. It is worth making the basic point that all the equipment discussed contains separation built into the washer and the wash solution is reused for many wash cycles. The exact degree of recycling depends upon the user's wishes.

Improved soil separation can be added to the washer and the wash solution life may be usually limited by microbiological deterioration. A more economic approach is to drain and separate at a dedicated plant. Concentration of the soil to 30-40% solids is relatively easily achievable using membrane separation albeit at a substantial cost. The water phase is relatively innocuous with many of the organic or biodegradable normal sewage treatment. The biocide is normally spent by the time discharge occurs. There is some risk of carrying chelated heavy metals into the waste water but only if they are readily mobilised from the soils being cleaned. Most chelant is adsorbed onto soil particle surfaces or carries calcium or magnesium in solution.
CFC cleaning was originally introduced to remove corrosive flux residues from circuit boards after soldering. Fluxes are required to remove oxidation from the circuit board and components, immediately after soldering. The idea behind no-clean fluxes is to use oxide removing systems that will not harm the circuit board, even if they remain on the board for the product's entire life. The main advantages of this technology are: relative cost, and that there are few environmental and safety concerns.

Introduction

There are a variety of ways to eliminate the need for CFC cleaning in the electronics industry. A technology which has been adopted by many firms are flux systems that do not require cleaning after soldering has been finished.

CFC cleaning was originally introduced to remove corrosive flux residues from circuit boards after soldering. CFCs were considered the ideal solvent because they are not flammable, safe for human use, excellent for dissolving oily substances and inexpensive.

Fluxes are required to remove oxidation from the circuit board and components just prior to soldering. The idea behind no-clean fluxes is to use flux systems that will not harm the circuit board, even if they remain on the board for the product's entire life. The result of this is that the manufacturing philosophy and all the process steps have to be reexamined.

Advantages and Disadvantages of Other CFC Replacements

Besides no-clean fluxes there are several other technologies available: HCFC Solvents, Aqueous and Semi-aqueous Systems. These alternative technologies, unlike no-clean fluxes, use a solvent system of some sort to clean. These systems will not be examined in any detail in this paper. A few notes have been added to advise why an individual may prefer to work with a no-clean system.

The advantage of these alternatives are that there are few, if any, changes required to the steps before and after soldering and cleaning. By cleaning the circuit boards one is able to avoid potentially damaging residues from remaining on the circuit assemblies. The main disadvantage of these technologies is the