TECHCOMMENTARY

INDUCTION HEAT TREATMENT

Published by the EPRI Center for Materials Fabrication Vol. 2, No. 2, 1985 Reprinted March, 1990

Using Induction Heat Treatment to Obtain Special Properties Cost Effectively

Heat treatment is often one of the most important stages of metal processing because it determines the final properties that enable components to perform under such demanding service conditions as high load, high temperature, and adverse environment. This **Tech-Commentary** illustrates how you can use the special features of nduction heat treatment, such as its speed and selective heating capability, to produce quality parts cost effectively. It will answer such questions as: What are the advantages of induction heat treatment? What heat treatments can I conduct with induction? What are some typical parts and materials that are induction heat treated? What properties can I obtain with induction heat treatment?

The differences between induction and conventional furnace-based heat treating processes and some advantages of induction heating are discussed in **TechCommentary** Vol. 2, No. 1. Advantages specific to induction heat treating are:

Speed — In heat treatment, the higher heating rates play a central role in designing rapid, high-temperature heat treating processes. Induction heat treating of steel may take as little as 10 percent or less of the time required for furnace treatment. Short heating times also lead to less scaling for materials such as steels that oxidize readily at high heat treating temperatures.

Selective Heating — Controlling the heating pattern by selecting the right induction equipment allows surface and selective heat treatments that yield an attractive blend of properties (e.g., high strength and toughness). Such treatments are not feasible with furnace processes, which are slow and heat the entire workpiece.

Energy Savings — In addition to eliminating dwell periods, induction heat treating techniques put energy only where needed, improving energy efficiency.

Increased Production Rates — Rapid heating often increases production and reduces labor.

HEAT TREATING - PROCESS OVERVIEW

Heat treatment is the controlled heating and cooling of a solid metal or alloy to obtain desired properties. Depending on the material and its intended use, heat treatment can improve such characteristics as formability, machinability, and service performance. Typical heat treating operations include:

- Annealing — used to soften metals to improve formability and machinability.
- Hardening — used to increase the strength and deformation resistance of metals (such as steels).
- Tempering — used to increase the toughness of hardened metals and thereby improve their resistance to brittle, catastrophic failure in high-stress, high-integrity applications.

A glossary at the end of this **TechCommentary** precisely defines these and other important heat treating terms.

There are two broad categories of heat treating processes — those involving **indirect** heating and those using **direct** heating. With indirect methods, heat is produced in a furnace by burning a fuel or by converting electrical energy into heat by passing a current through resistance heating elements. This energy is then transferred to the workpiece by radiation, convection, or conduction. By contrast, direct heating methods, including induction, direct resistance, and flame heating, supply heat directly to the workpiece. An in-depth discussion of how induction heating works is included in **TechCommentary** Vol. 2, No. 1.

Types Of Induction Heat Treatments

You can utilize the speed and selective heating characteristics of induction processes for:

Hardening of Steels — Steels are hardened by heating to austenitizing temperatures and then quenching. The speed of induction heating and minimal soak time mandate higher austenitizing temperatures than those used with furnace processes (Table 1). Depth of austenitization is

Percent Carbon	Furnace Heating, F (C)	Induction Heating, F (C)
0.30	1550 to 1600 (845 to 870)	1650 to 1700 (900 to 925)
0.35	1525 to 1575 (830 to 855)	1650 (900)
0.40	1525 to 1575 (830 to 855)	1600 to 1650 (870 to 900)
0.45	1475 to 1550 (800 to 845)	1600 to 1650 (870 to 900)
0.50	1475 to 1550 (800 to 845)	1600 (870)
0.60	1475 to 1550 (800 to 845)	1550 to 1600 (845 to 870)

Table 1 Austenitizing Temperatures For Carbon Steels

easily controlled so that parts can be surface or through hardened.

Tempering of Steels — Tempering of hardened steels is a function of both time and temperature. Induction tempering uses shorter heating times (usually only seconds) and higher temperature to produce results equivalent to furnace tempering treatments that often require hours.

Normalizing — Since normalizing requires heating to a high temperature followed by air cooling, it is an ideal application of induction heating. Induction normalizing treatments are often used for products that can be processed on a continuous basis, such as pipe.

Weld Seam Annealing — The speed and selectivity of induction heating can be called on for local stress relief annealing of welds in sheet metal, tubular, and other kinds of products.

Recrystallization Annealing — Annealing treatments for sheet metal have been carried out successfully using a new process called "transverse flux" (TFX) induction heating, in which sheet is fed continuously through a specially designed coil. Total heating time is only a few seconds, compared to many hours for conventional furnace or batch annealing of coils of sheet metal. Moreover, the fine temperature control with induction heating permits partial as well as full recrystallization annealing, depending on the annealing temperature chosen. Thus, a range of properties, not obtainable with batch annealing, is possible.

Induction Heat Treating Applications And Materials

You can use induction heat treatment for a wide range of parts. The brief list of common applications that follows is only representative of its potential use.

Surface Hardening and Tempering of Steels:

- Transportation — crankshafts, camshafts, axle shafts, transmission shafts, splined shafts, universal joints, gears, valve seats, wheel spindles, bearings.
- Machine tools — lathe beds, transmission gears, shafts.
- Metalworking, hand tools — rolling mill rolls, pliers, hammers.

Through-Hardening and Tempering of Steels:

- Oil-country tubular products, structural members, spring steel, chain links.

Annealing:

- Longitudinally welded steel tubes, nonferrous sheet metals, ferrous and nonferrous wire, steel pipes, tanks.

Induction heat treating is also useful for a wide range of materials, but steel parts comprise the largest portion of induction heat-treated components. Some typical induction heat-treated steels are

- Medium-carbon steels, such as 1030 and 1045, used for welded tubing, automotive shafts, and gears
- High-carbon steels, such as 1070, used for hand tools
- Alloy and stainless steels used for bearings, automotive valves, and machine tool components
- Tool steels, such as M2 and D2, used for cutting tools and metal-working dies.

The induction annealing of aluminum and its alloys is certainly feasible, but, at present, nonferrous alloys are induction heat treated less often than steels. Pending the development of an information base on process economics, heat treatments for titanium and nickel-base alloys, which are readily heated by induction, could become a reality in the future.

Technical And Economic Considerations

Determining whether induction heat treatment is suited to your needs requires evaluation of such technical factors as:

Workpiece Size and Shape — These influence the shape of the induction coil to be used. It is easiest to design coils for symmetric parts. However, induction heat treating is readily applied to irregularly shaped components by using special coil designs.

Subsequent Processing — Should permit easy integration of induction heat treating. This includes, for example, the design of quench stations following steel hardening operations. The high speed of induction heating may accommodate machining operations on the same processing line.

Metallurgical Condition — Must the part meet special service requirements that induction heating can provide, such as a blend of high strength and toughness? Some of the properties and characteristics of induction heat treated parts are discussed below.

In addition to evaluating technical feasibility, you must also determine if induction heating is cost effective when compared to other techniques. Important economic factors in your decision should include production lot size, equipment and energy costs, labor requirements, scale and scrap losses, and floor space requirements. The way each of these elements figure in an overall cost analysis is discussed in detail in **TechCommentary,** Vol. 2, No. 1.

Properties Of Induction Heat Treated Parts

The largest amount of property information on induction heating is for hardened and tempered steel parts. Such data indicate that induction through heat-treated parts have mechanical properties similar to

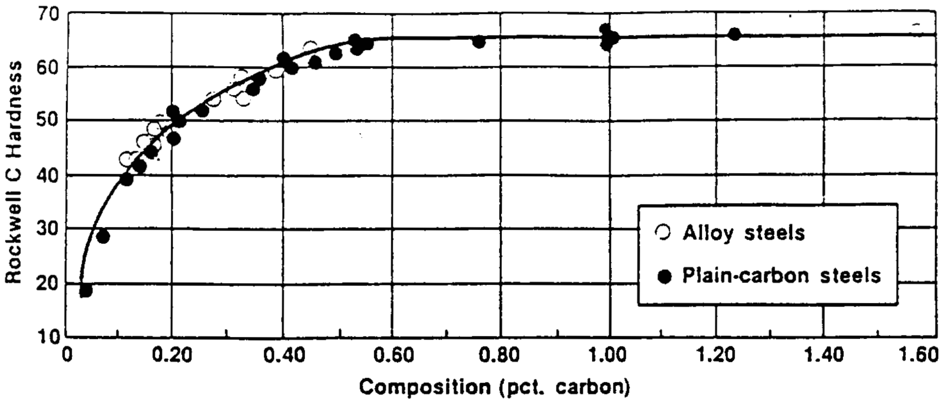

Figure 1 Hardness Of As-Quenched Martensite As A Function Of Its Carbon Content

those heat treated in furnaces.

In many applications, however, surface hardened and tempered steel parts surpass their furnace treated counterparts. This is because surface induction heating leads to:

- A hard case and a soft core, which provide a good blend of strength and toughness not attainable with furnace through heating. Further, because the hardness of as-quenched steels depends only on carbon content (Figure 1), this combination of properties can be obtained in inexpensive carbon steels. Induction heat-treated carbon steel parts can be used in many applications that require alloy steels with good toughness, which are through heat treated in furnaces.
- Compressive residual stresses at the surface, which are important in combination with the surface hardness. These residual stresses arise primarily from the density difference between the hard martensite layer and the softer interior layer of pearlite or bainite in surface hardened parts.

The combination of a hard surface, compressive residual stresses, and a soft core results in excellent wear and fatigue resistance. Improvement in bending fatigue when compared to furnace treatments is shown in Figure 2 for axle shafts. The attributes of induction treatment are particularly attractive in bending fatigue in which high levels of tensile stress are generated at the surface, and no stresses are imposed at the center. Here, the property distribution in the surface hardened part is well matched with the demands placed on it in service. Another example is the wear resistance afforded gear teeth by selective surface hardening. Properties of induction surface hardened parts are discussed further in **Tech-Commentary** (Vol. 2, No. 3).

Heat Treating Processes That Compete With Induction

Considerations of speed, selective heat treating requirements, and process economics are often sufficient to establish whether you should use induction or conventional furnace-based methods for through heat treatment. On the other hand, if you've determined that surface hardening is necessary, there are a number of other processes to consider. These include conventional **carburizing** and **nitriding, ion-nitriding, laser hardening** and **electron beam hardening.**

Carburizing and nitriding are well established technologies in which surfaces are alloyed with carbon or nitrogen by placing parts in a gaseous or liquid environment. The alloying results in surface hardening. Cost data from commercial heat treaters indicates that the overall cost for induction hardening is much less than for carburizing, salt bath nitriding, or gas nitriding. (The cost ratio for the 4 processes in the order listed is 0.11:2.5:1.75:8.) Thus, if your part geometry and production volume allow the use of induction, it is the preferred surface hardening method from a cost standpoint.

Ion-nitriding, laser hardening, and **electron-beam (EB) hardening** are emerging technologies that are

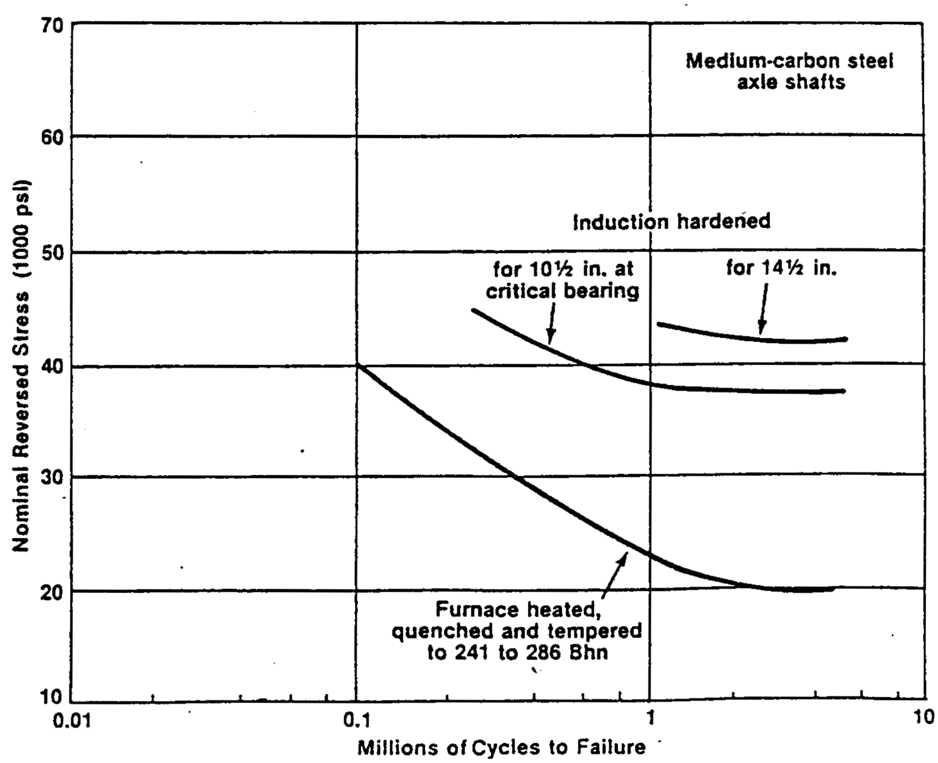

Figure 2 Bending Fatigue Response Of Medium-Carbon Steel Tractor Axles Which Were Either Furnace Hardened Or Induction Hardened

used to obtain shallow case-hardened depths (0.02 in. or less). Ion-nitriding is similar to other nitriding processes except that a glow-discharge method is employed.

Laser and EB techniques both use extremely high-energy input rates that austenitize a very thin surface layer in a fraction of a second. The bulk of the substrate remains cool and provides an adquate heat sink for "self-quenching". Advantages include:

- Minimal workpiece distortion
- Ability to selectively harden portions of a surface and to control the process in general
- Ability to harden areas inaccessible to conventional induction techniques
- Repeatability
- High speed.

According to a recent American Society for Metals (ASM) survey, ion-nitriding offers the greatest challenge to induction heating for purposes of surface hardening. Laser and EB processes are also expected to satisfy some of the applications now handled by induction, particularly those for which induction coils are difficult to design. Nevertheless, in situations in which case depths of 0.02 to 0.04 in. are required, induction systems that produce very high-power inputs per unit of surface area (i.e., "high intensity" induction setups) can compete effectively because of lower equipment cost, higher productivity, less maintenance, and lower floor space requirements. For example, in typical industrial applications, a 2 to 3 kilowatt laser, costing approximately $250,000 is required. This is about 3 times the cost of comparable induction equipment. Electron-beam hardening also has some important limitations, such as the need for a vacuum atmosphere.

Design Of Induction Heat Treatment Processes

To make induction heat treatment work for you, carefully select equipment and understand the metallurgical variables that control heat treating response. The most important equipment parameters are **coil design, generator frequency,** and applied **power density.**

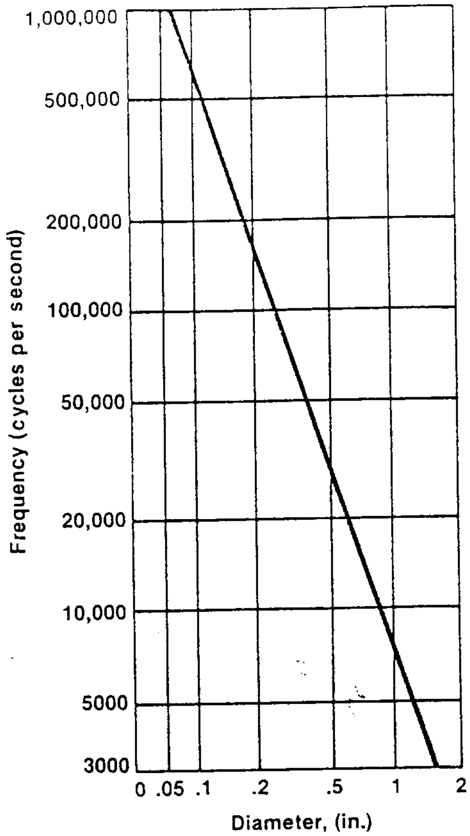

Figure 3
Relation Between Diameter Of Round Steel Bars And Minimum Generator Frequency For Efficient Austenitizing Using Induction Heating

Coil Design — Solenoidal coils are easily designed for round parts. For more complex parts, design procedures are described in induction heating textbooks or can be provided by equipment manufacturers.

Generator Frequency — This is determined by the material, part size, and the need for through or surface heating. Low frequencies, which provide large "penetration" depths of the induced eddy currents, are used for through heat treating. High frequencies are used for surface heat treating. The minimum frequencies for efficient through austenitizing of steel bars are shown in Figure 3. Frequencies for surface hardening of steels are chosen to ensure penetration depths of about twice the required hardened depth. Other variables, such as power density, are important in selecting frequency in these instances as well and are discussed in **TechCommentary,** Vol. 2, No. 3.

Power Density (or power per unit of surface area) — The same power input can lead to a low heating rate for a large part but a high heating rate for a small part. As with frequency, power density level is selected based on the need for through or surface heat treating. The schematic diagram in Figure 4 illustrates the typical temperature versus time behavior for an induction heated part and is useful in explaining power density effects. Because the magnitude of the eddy currents are greatest at the surface and least at the center, the surface heats more rapidly. After an initial transient, the difference in temperature remains fixed. This difference represents an equilibrium between heat input via induction and heat transfer between the surface and center by conduction. As such, it is a function of the applied power density and workpiece electrical and thermal properties. For through heating and heat treating, lower power densities of 0.1 to 0.5 kW/in.^{2} are recommended to ensure a more or less uniform heating pattern. High power densities (approximately 10 to 20 kW/in.^{2}) are needed for surface heating and heat treatments of steel.

Using data on coil design and power supply requirements, you can figure out where the heating power is going to be located in your heat treating process. To ensure success, however, it is important to understand the metallurgical properties of the workpiece and how these interact with your heating cycle. Of utmost importance is the design of the necessary time-temperature cycles, which are typically quite different from those for furnace heat treatments.

The data in Table 1 reveal that higher temperatures are employed for induction austenitizing of steels. You need these to compensate for short or zero soak times. Similarly, short-time tempering treatments involving short or zero soak time can be designed around induction heating processes by using the so-called tempering parameter,

$$\mathbf{T}(14.44 + \log_{10}\mathbf{t}),$$

where **T** is the tempering temperature in degrees Rankine and **t** is the tempering time in seconds. An induction tempering treatment

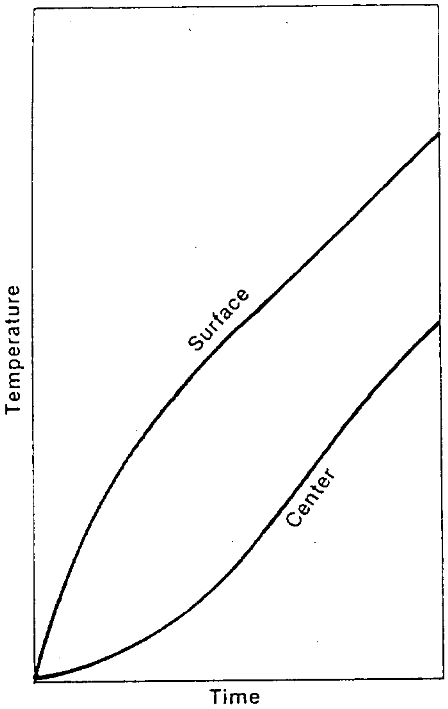

Figure 4
Schematic Illustration Of The Surface And Center Temperature Histories Of A Bar Heated By Induction (Note that, following an initial transient, the surface-to-center temperature difference is constant during the heating cycle.)

whose tempering parameter is equivalent to that for a longer-time, lower-temperature treatment will give a part with equivalent properties. The application of this concept is discussed further in **TechCommentary,** Vol. 2, No. 4.

A final factor that warrants consideration in process design is the starting condition of the workpiece. This is particularly important for steels that are to be hardened. In these cases, austenitizing behavior will be affected greatly by the starting microstructure. An example of this microstructure effect is seen in Figure 5. As shown here, when using the same induction heating parameters, the case hardened depth for a 1070 steel bar increases as the starting structure becomes finer: quench and tempered = fine martensite structure, normalized = fine pearlite with thin lamellar carbides, and annealed = structure with coarse, difficult-to-dissolve spheroidal carbides.

Such variations in induction heat treatment results can be overcome

Glossary Of Heat Treating Terms*

Alloy Steel — Steel containing significant quantities of alloying elements (other than carbon and the commonly accepted amounts of manganese, silicon, sulfur, and phosphorous) added to effect changes in the mechanical or physical properties.

Annealing — Heating to and holding at a suitable temperature and then cooling at a suitable rate for such purposes as reducing hardness, improving machinability, facilitating cold working, producing a desired microstructure, or obtaining desired mechanical, physical, or other properties. Specific types of annealing processes include:

Recrystallization annealing — Annealing cold or hot worked metal to produce a new grain structure without phase change.

Spheroidization annealing — Heating and cooling to produce a spheroidal or globular form of carbide in steel.

Stress relief annealing — Heating to a suitable temperature, holding long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses.

Austenitizing — Forming of the face-centered-cubic austenite phase in steel by heating above the transformation temperature range. Process forms the basis of hardening of steels.

Bainite — A decomposition product of austenite consisting of an aggregate of ferrite and carbide. In general, it forms at temperatures lower than those where very fine pearlite forms and higher than that where martensite begins to form on cooling. Its appearance is feathery if formed in the upper part of the temperature range; acicular, resembling tempered martensite, if formed in the lower part.

Carbon Steel — Iron alloy containing carbon up to about 2 percent and only residual quantities of other elements except those added for deoxidation, with silicon usually limited to 0.60 percent and manganese to 1.65 percent. Also termed plain-carbon steel.

Cementite — A compound of iron and carbon found frequently in steels known chemically as iron carbide and having the approximate chemical formula Fe_3C.

Ferrite — A solid solution of 1 or more elements in body-centered cubic iron; the solute is generally assumed to be carbon unless designated otherwise.

Hardenability — In steels, the property that determines the depth and distribution of hardness induced by austenitizing and quenching. Hardenability is a function of alloy composition and quenching medium.

Hardening — Increasing the hardness by suitable treatment, usually involving heating and cooling. For steels, this typically consists of austenitizing followed by cooling to form pearlite, bainite, or martensite, or a combination of these constituents.

Martensite — A metastable phase of steel formed by a transformation of austenite below the M_s temperature and composed of a body-centered tetragonal lattice. Its microstructure is characterized by an acicular, or needle-like, pattern.

Microstructure — The structure of polished and etched metals as revealed by a microscope at a magnification greater than 10 diameters.

Normalizing — Heating a ferrous alloy to a suitable temperature above the transformation range and then cooling in air to a temperature substantially below the transformation range.

Pearlite — A lamellar aggregate of ferrite and cementite, often occurring in steel and cast iron.

Quench Hardening — Hardening a ferrous alloy, such as a steel, by austenitizing and then cooling rapidly enough so that some or all of the austenite transforms to martensite.

Tempering — Reheating a normalized or quench-hardened ferrous alloy such as a steel to a temperature below the transformation range and then cooling at any rate desired.

Transformation Temperature — The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range.

*Source: *Metals Handbook*, Vol. 1, Eighth Edition, American Society For Metals, 1961.

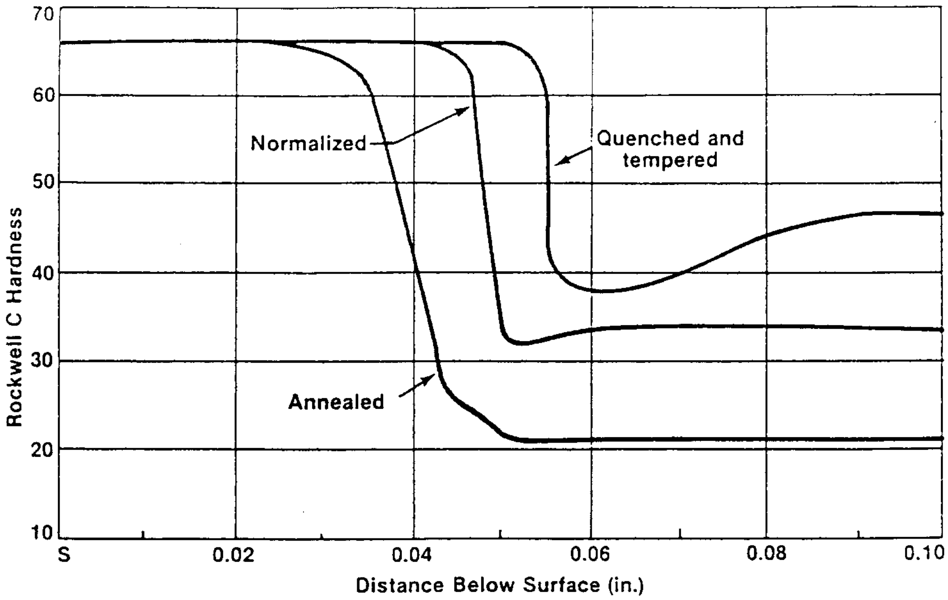

Figure 5 Effect Of Starting Microstructure In 1070 Steel Bars On Surface Hardening Response Using A 450 kHz Induction Generator Operated At A Power Density Of 2.5 Kilowatts Per Square Centimeter (15.9 kilowatts per square in.)

by determining (on a trial-and-error basis) modified peak temperatures or heating rates for your particular alloy and expected variations in starting condition.

In Summary

Induction heat treatment is applicable to hardening, tempering, normalizing, and annealing a wide range of parts, particularly in ferrous alloys — medium- and high-carbon steels, alloy and stainless steels, and tool steels. It is also finding increasing application in the nonferrous metals industry. Advantages include high heating rates, selective heating capability, improved production rates, and energy savings. Induction heat treatment can produce surface hardened parts with soft cores that exhibit excellent wear and fatigue resistance. However, satisfactory heat treatment requires careful selection of equipment and good understanding of the metallurgical variables involved. For surface hardening applications, there are a number of competing processes to consider. □

This **TechCommentary** provides an overview. It is intended to familiarize you with the important applications of induction heat treatment. If you are interested in a more detailed background, please refer to subsequent issues of **TechCommentary** on "Surface and Selective Heat Treatment" (Vol. 2, No. 3), "Induction Tempering" (Vol. 2, No. 4), and the sources listed below.

The Center for Materials Fabrication (CMF) is operated by Battelle's Columbus Division. Basic funding is provided by the Electric Power Research Institute, a nonprofit institute that conducts research and development on behalf of the United States electric utility industry.

The Center's mission is to assist industry in implementing cost- and energy-efficient electric-based technologies in the metals fabrication and related fields. **TechCommentary** is one communication vehicle that the Center uses to transfer technology to industry. The Center also conducts research in metal heating, metal removal and finishing, and fabrication.

This issue of **TechCommentary** was made possible through the cooperation of Battelle staff members Lee Semiatin, author; Jack Mortland, editor; Laura Cahill, publications coordinator.

Sources used in this issue of **TechCommentary** were:

Induction Hardening and Tempering, American Society for Metals, 1964, T.H. Spencer, et al.

Induction Heat Treatment of Steel, American Society for Metals, 1985, S.L. Semiatin and D.E. Stutz.

Metals Technology, Vol. 9, No. 12, pp. 493-498, The Metals Society, 1982, "Transverse Flux Induction Heating of Aluminum-Alloy Strip," R. Waggott, et al.

Sources for tables and figures were:

Transactions of ASM, Vol. 26, pp. 1-36, American Society for Metals, 1938, "Quantitative Hardenability," J.L. Burns, T.L. Moore, and R.S. Archer.

Transactions of ASST, Vol. 12, p. 871, 1927, W.P. Sykes and Z. Jeffries.

High-Frequency Induction Heating, McGraw-Hill Book Company, 1950, F.W. Curtis.

Basics of Induction Heating, John F. Rider, 1960, C.A. Tudbury.

Induction Hardening and Tempering, American Society for Metals, 1964, T.H. Spencer, et al.

Applicable SIC Codes

33— 12, 15, 16, 17, 21, 34, 41, 51, 53, 54, 55, 56, 98, 99

34— 11,12, 21, 23, 25, 29, 41, 43, 49, 52, 62, 63, 71, 79, 83, 84, 89, 93, 95, 99

35— 23, 24, 31, 32, 33, 36, 41, 42, 44, 45, 46, 47, 62, 66, 67, 68, 92, 99

36— 21

37— 11, 14, 21, 24, 28, 43, 51, 61, 64, 69, 95, 99

For further information on Center programs, write or call

CENTER FOR MATERIALS FABRICATION
An EPRI R&D Applications Center
505 King Avenue • Columbus, Ohio 43201-2693
(614) 424-7737