Be Aware of the 'Fine Print' In the Science of Metallurgy of Induction Hardening: Part 2

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Certain metallurgical phenomena and principles of heat treatment frequently are incorrectly assumed or improperly used in the application of induction hardening.

We are reminded in many aspects of our lives today to read the "fine print" contained in manuals, warrantees, instructions, etc., so that we don't miss important information. Important information also is often overlooked in the science of metallurgy. While there is no fine print, there are metallurgical "fine points" and subtleties, which require paying close attention. In many cases, certain metallurgical phenomena and principles of heat treatment are incorrectly assumed or improperly used in induction hardening. It is important to look closer at the "fine points" of metallurgical theory to ensure optimal results. To illustrate this, following are additional examples to those discussed in Part 1 of this article (March 2005 *IH*).

Is it always possible to obtain a fully martensitic structure of noneutectoid plain carbon steels using severe water spray quench?

In hardening applications, the ability to obtain a certain degree of martensitic structure is often the measure of how successful the heat treating process was. Martensite is a supersaturated solid solution of carbon in ferrite with a body-centered tetragonal crystalline (BCT) structure. Upon rapid cooling, carbon is trapped in the crystal structure. The high hardness developed when steel is transformed to martensite is due to distortion in the transformation from FCC (austenite) to BCT

martensite crystalline structure [1-3]. Martensite formation is governed by a shear-type (diffusionless) transformation of austenite; that is, the transformation occurs almost instantaneously upon reaching a certain temperature.

If the continuous cooling transformation (CCT) diagram of steel is shifted far to the left, the cooling curve will enter the upper transformation start region regardless of quench severity, preventing the capability to obtain an entirely martensitic microstructure. In such cases, the final microstructure of the hardened layer will consist of a combination of martensite and upper transformation products (e.g., pearlite and banite) regardless of the severity of the quench from austenitic temperature down to ambient temperature. Although a fully martensitic structure might not be obtained, the amount of upper transformation products can be appreciably small and might not noticeably affect component mechanical properties in certain applications.

Martensitic transformation occurs over a temperature range between the M_s (martensite start) to M_f (finish), which depends on the particular steel chemical composition, and from practical perspective, cannot be changed by varying quench severity. If cooling upon quenching is interrupted at a certain temperature within the martensite transformation range, no further transformation to martensite will occur. Martensite transformation resumes upon further cooling to a lower temperature.

Figure 1 shows that M_s-M_f temperature range is directly related to the steel's carbon content. The carbon content and actual amount of martensite formed exclusively determine the maximum hardness of given steel. In the range of 0.2 to 0.65% carbon, the hardness of the steel is proportional to the carbon content.

M_f temperatures for plain carbon steels with high carbon content, cast irons and some alloy steels are well below room tem-
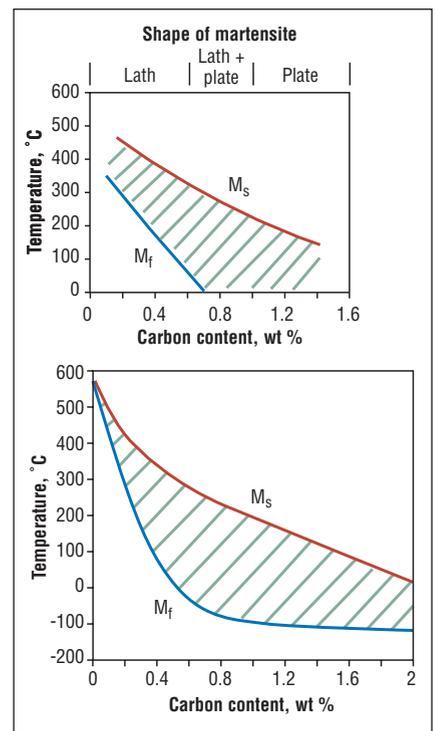

Fig. 1. Influence of carbon content on M_s and M_f temperatures. Source: top (Ref. 4,5); bottom (Ref. 6).

perature. Thus, even if quench severity is sufficient to miss the upper transformation region of the CCT diagram, a fully martensitic structure will not be obtained within the hardened layer. The existence of a noticeable amount of untransformed, or retained, austenite will be unavoidable (Fig. 2). Cryogenic treatment can be used to transform the retained austenite into martensite. Note that a full untempered martensitic structure has low ductility [1].

The inability to obtain a fully martensitic structure is directly related to not having homogeneous austenite. As mentioned in Part 1 of this article, rapid induction heating can result in inhomogeneous austenite with a ferritic/pearlitic network (dependent on chemical composition, prior microstructure and process specifics), which remains in the as-quenched structure, preventing a fully martensitic structure.

Nonuniform distribution of carbon is another characteristic of inhomogeneous austenite. After fast heating, a ferrite/pearlite network might not exist, but the austenite phase could consist of localized regions of enriched carbon and reduced carbon. Since both M_s and M_f temperatures depend on carbon content, austenite areas of high and low carbon concentration will have different critical cooling rates (CCT curves) resulting in different transformations to martensite. This may lead to the appearance of alternative products within the martensitic structure.

Carbon content not only influences achievable surface hardness and case depth, but also the transition zone. For example, eutectoid steel always has a shorter transition zone compared with a hypoeutectoid steel (assuming temperature distribution and quenching conditions are the same).

Can results of Grossmann's hardenability tests and Jominy end-quench tests be directly applied to selective hardening?

Hardenability is an important property of steel and cast iron, defining the ability of the metal to be hardened to a certain depth. It is measured as the distance from the surface where certain hardness can be obtained or a specific percentage of martensite can be formed (e.g., 50 HRC or 50% martensite).

When discussing hardenability, it is important to recognize factors that influence hardness distribution in through hardening compared with surface hardening.

Through hardening (hardening a workpiece through its entire cross section) typically requires heating the part uniformly to the austenitizing temperature range and quenching to ambient temperature. During quenching, the cooling rate at the surface always is more intense compared with the rate at internal locations; particularly compared with the rate at its core. For a thin part, the cooling intensity at the core might be severe enough to miss the upper transformation region of the continuous cooling diagram and to form a sufficient amount of martensite in core, resulting in a relatively uniform through-hardened pattern. Also, because the cooling rate at the surface is always more intense than that at the core, more martensite forms at the surface and subsurface than in the core, resulting in a higher hardness at the surface (assuming that surface has not been overheated and severe oxidation and/or decarburization did not occur).

At larger diameters or thicknesses, the depth of the hardened layer (hardened depth) also increases. In addition, because the core is at a greater distance from the quenched surface, thermal conductivity provides less intense cooling of the core during surface quenching. At a certain point, the CCT curve representing core cooling conditions during surface quenching shifts farther to the right (Fig. 3), eventually passing through an area where transformation starts at a temperature higher than the M_s temperature. Thus, depending on the cool-
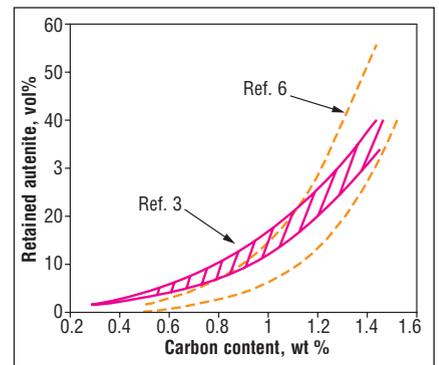
Fig. 2. Influence of carbon content on volume of retained austenite
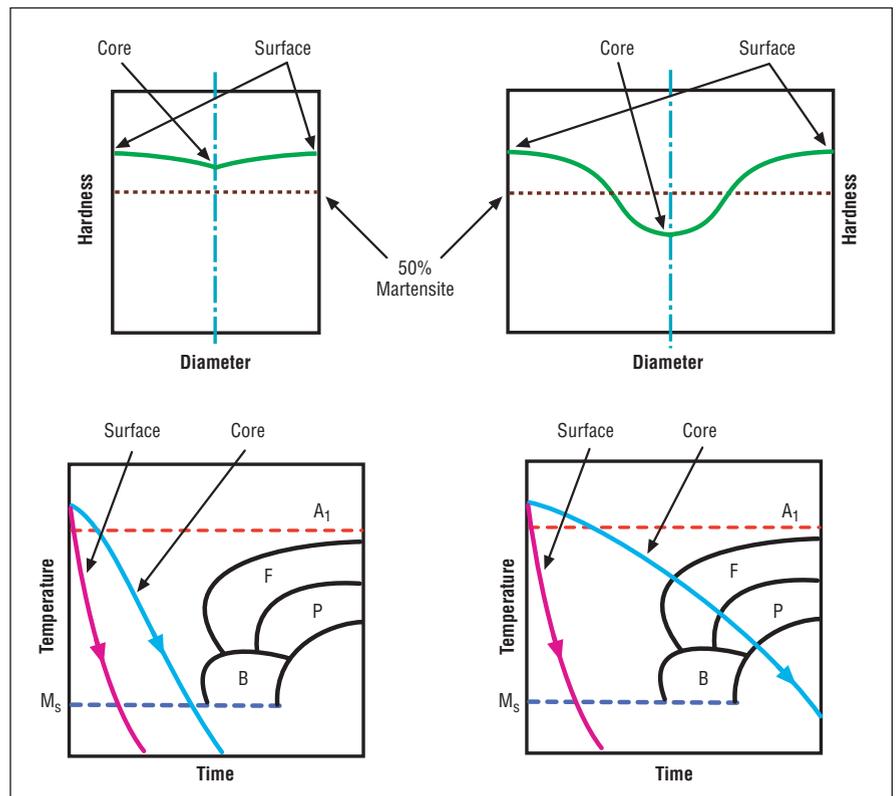
Fig. 3. Influence of test specimen diameter on hardness profile and core cooling rate [1]

ing rate, a certain amount of upper-transformation products (i.e., bainite, pearlite, ferrite) form within the core leading to a softer core compared with the surface.

Surface hardening (case hardening) involves a relatively short heat up time and a pronounced skin effect, and core temperature does not rise significantly during the heating stage [1]. Upon quenching, the cold core provides an additional cooling effect on the case hardening area compared with through-heated parts. A more intensive quench increases hardness and steel hardenability, and dramatically increases the formation and distribution of residual stresses [1].

Hardenability tests

Techniques used to determine steel and cast-iron hardenability include Grossmann's hardenability test and the Jominy end-quench test–the most widely used tests [1-3]. Grossmann's test involves the concept of critical diameter. Cylindrical bars having different diameters are cooled from a specific austenitizing temperature down to ambient temperature using a given quench medium. For a particular quenchant, a bar having 50% martensite at its core would correspond to the critical diameter D_{cr}. The critical diameter is influenced by chemical composition, grain size and homogeneous austenite, which can be relatively easily defined. However, quenching condition often is the least defined factor, particularly in the case of induction hardening. Cooling severity during spray quenching depends on a combination of factors including quenchant type and purity; concentration; quenching temperature, pressure and flow rate; quench block design; number and distribution of quench holes, orifice size and density; spray impingement and part rotation.

The Jominy end-quench was developed to overcome the complexity of the Grossmann's hardenability test. In the test, a 25 mm OD by 100 mm long (~1 in. by 4 in.) cylindrical specimen is uniformly heated to achieve homogeneous austenite and spray quenched on one end, producing a longitudinal hardness distribution as a function of the distance from the quenched end. Both test methods require some degree of caution for induction hardening

(particularly induction surface hardening) due to the assumptions in measurements that have been done.

The standard Jominy end-quench test is suitable for moderate cooling rates. Therefore, it can provide misleading results at cooling rates 150°C/sec (270°F/sec) or higher experienced with a majority of induction hardening applications. Quench severity exceeds 1000°C/sec (1830°F/sec) in some induction hardening applications.

In standard hardenability tests, a specimen is heated to the austenitic temperature and held long enough to ensure forming homogeneous austenite. By comparison, induction hardening involves intense heating with a relatively short or no holding time, which can produce inhomogeneous austenite with corresponding differences in the hardenability curves. Intense heating during induction hardening shifts the A_1 and A_3 critical curves toward higher temperatures [1,7]. Quenching from temperatures that are often 100 to 180°C (180 to 325°F) higher than the temperature used during hardenability tests can result in appreciable errors.

Conventional hardenability curves also are modified by the cold core serving as a heat sink and by higher surface and subsurface quenching severity. The cold core can have a self-quenching (mass quenching) effect, which allows the elimination of liquid spray quenching in some hardening applications with a small case depth.

Hardenability tests are primarily oriented toward cylindrical shape specimens versus other shapes, which make it difficult to apply test results to parts having complex shape. Data obtained from a standard Jominy or Grossman test should be used for reference purposes only.

Are the procedures for choosing process parameters for induction hardening of steels and cast irons identical?

One of the most common applications of induction heat treatment is hardening cast iron parts such as camshafts, crankshafts, liners, gears, rollers, etc. Figure 4 shows an induction system used to heat treat cast iron camshafts. Induction surface hardening of cast irons has many similarities to

Fig. 4. Compact system for hardening cast iron camshafts. Courtesy of Inductoheat Inc.

induction hardening of carbon steels, but there are some significant differences [1].

Cast irons comprise a family of materials represented on the right side of the Fe-FeC_3 phase diagram having a high carbon content (2+%) and a wide range of properties [1,7]. Gray, ductile (nodular) and malleable and compacted-graphite iron (to a lesser extent) are induction hardened.

Gray iron contains carbon as graphite in flake form (Fig. 5), which combined with the high carbon content makes gray iron castings brittle and hard, with low tensile strength and a poor ability to withstand appreciable thermal shock and shock load. Due to their relatively high silicon contents, commercial cast irons should be considered as at least ternary Fe-C-Si alloys.

As a result, all critical temperatures of cast irons differ from those shown in the right side of the Fe-Fe$_3$C diagram [1].

The ability of gray irons to be hardened depends on the type of matrix (i.e., ferritic, ferritic-pearlitic or pearlitic) and the amount, size, shape, and distribution of graphite flakes. A pearlitic matrix provides a better response to induction hardening of gray irons. Being brittle, gray iron may present certain challenges to induction hardening due to a tendency toward cracking from fast heating and intense cooling [1,9,10]. Preheating and soft quenching are often used. However, some gray iron parts have been successfully hardened using short heat time (less than 2 seconds) and quenching using plant water (Fig. 6).

In contrast to gray irons, ductile irons have carbon particles in the form of graphite nodules, which serve as crack arresters. This gives ductile irons some advantages over gray irons including ductility, relatively high tensile and bending strength and moderate elongation. An induction hardened ductile (nodular) cast iron crankshaft with case hardness pattern and microstructure, transition zone and green core is shown in Fig. 7.

Ductile (nodular) irons offer a wide range of properties. Five subgroups of ductile iron are ferritic, pearlitic-ferritic, pearlitic, martensitic and austempered ductile irons. Induction hardening is usually applied to martensitic, pearlitic and, to a lesser extent, pearlitic-ferritic ductile irons. Martensitic ductile iron requires the lowest hardening temperatures, shortest heat-up time and provides well-defined, crisp hardness patterns with a relatively shallow transition zone [1].

Being inherently strong, ductile irons can handle much greater stresses than gray irons upon heating and quenching without cracking. However, the presence of graphite nodules as crack-arresters does not guarantee ductile iron castings will not crack during intensive heating or/and severe quenching.

A temperature range of 860 to 960°C (1580 to 1760°F) is typical for induction hardening of iron castings. Besides carbon and silicon, all commercial cast irons also have other intentionally added alloying elements and residual impurities that could affect critical temperatures.

A key metallurgical difference between steels and cast irons that causes many problems in selective hardening is matrix carbon content versus total carbon content (CE) [8]. In steels, carbon content is fixed by chemical composition and cannot exceed this value in a fully austenitic condition. In contrast, cast irons have a carbon "reserve" in the primary graphite particles, which can cause localized increasing amounts of carbon to dissolve into the austenite matrix at higher austenitizing temperatures. This high (and variable depending on temperature) matrix carbon content is the most critical metallurgical factor in the selective hardening of cast irons, and lies at the root of problems such as excessive retained austenite, coarse martensite and unusual hardness patterns. Alloying elements can affect hardenability and retained austenite (by decreasing M$_s$ temperature) in steels, but matrix carbon content in cast irons have an overwhelming effect.

Ferritic ductile iron typically is not a good candidate for induction hardening due to the inability to transform low carbon containing ferrite into martensite.
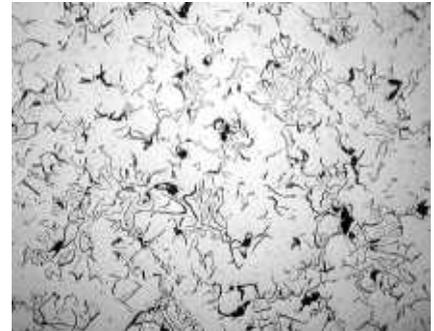

Fig. 5. Representative gray cast iron microstructure containing graphite flakes [9]

Fig. 6. Unitized machine with two independently operated heat stations and high-speed, servo-driven scanning assemblies for induction hardening the ID of gray iron cylinder liners. Production rate is 50 liners/h with a 0.8 mm (0.03 in.) case having 47-49 HRC as-quenched hardness. Courtesy of Inductoheat Banyard Ltd., Dorset, UK.

"Green" core
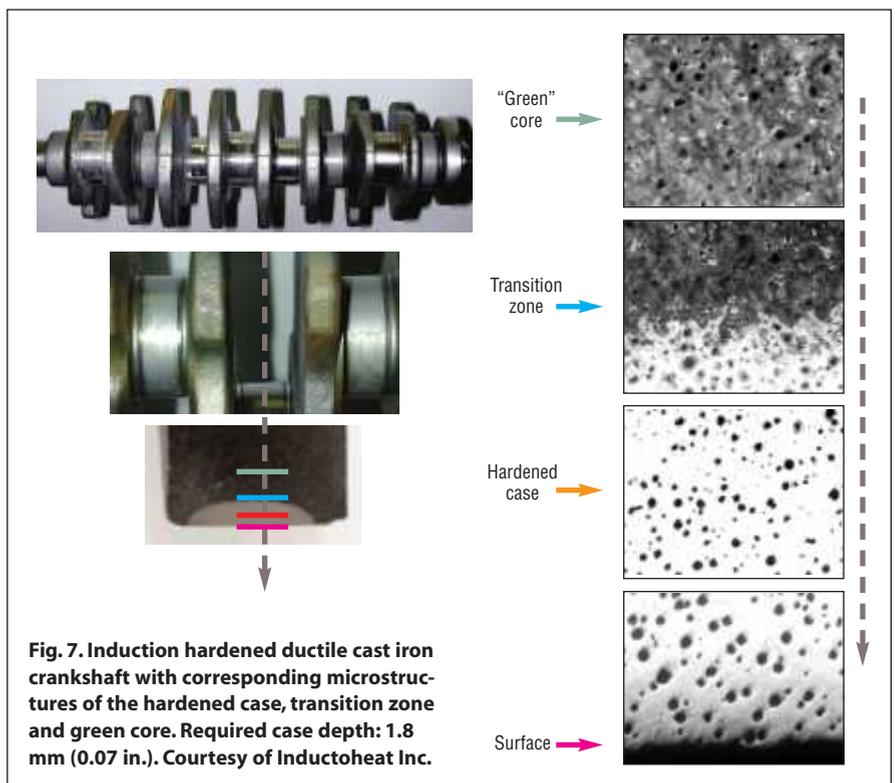
Transition zone

Hardened case

Surface

Fig. 7. Induction hardened ductile cast iron crankshaft with corresponding microstructures of the hardened case, transition zone and green core. Required case depth: 1.8 mm (0.07 in.). Courtesy of Inductoheat Inc.

However, intense induction heating and quenching can be used to improve the fatigue strength of ferritic ductile cast irons [12] from the ability to create localized martensitic areas and compressive stresses near the boundaries of graphite nodules due to carbon diffusion from graphite nodules into ferrite matrix.

Sections of varying thickness in complex shaped iron castings heat up at different rates, promoting thermal gradients and thermal stresses, which can result in distortion and crack development, particularly in locations having a drastic change of mass. Complications can arise when transitional thermal stresses combine with residual stresses from previous operations (e.g., casting, machining, honing, surface peening, etc.). Complex-shaped steel parts have less tendency to crack than complex cast iron parts. Stress relieving iron castings prior to induction hardening is often recommended to reduce the probability of cracking. Formation of stresses during induction hardening and tempering is discussed in [1]. Reasons for crack development during hardening cast irons and plain carbon or alloy steels are different [1,9,10]. For example, age strengthening can occur in gray iron castings but not in steel parts. If age strengthening occurs, some castings may harden relatively easily, while others may crack, even though heating and quenching conditions were identical.

A study of the age strengthening phenomenon [11] reported that aging at room temperature for about 60 days can strengthen gray iron castings by as much as 12%. The tensile strength-to-hardness ratio also increases because the hardness does not change with time. In a production environment, the time between casting and heat treating can be relatively short, and age strengthening will not occur. Thus, to ensure the reliability and repeatability of

a gray iron hardening operation, it is important to conduct a run-off using relatively "fresh" castings. Using castings that have been on the shop floor for some time for process development or run-off could result in hardening age-strengthened parts. Such results could be overly optimistic, and cracking might suddenly occur during a production run [1].

The response of cast irons to electromagnetic heating is different than that of steels. It is important to remember that in contrast to alternative heating processes, the intensity of induction heating is more sensitive to a chemical composition, and is directly related to the electromagnetic properties of the heated metal.

Electromagnetic properties of materials in a broad sense include magnetic permeability, electrical resistivity (electrical conductivity), saturation flux density, coercive force, hysteresis loss, permittivity, magnetic susceptibility and others. While all electromagnetic properties are important, this discussion is limited to the effect of electrical resistivity and relative magnetic permeability on the ability of metal to be heated by induction. Electrical resistivity and magnetic permeability have the most pronounced effect on performance of the induction heating system (Fig. 8).

Electrical resistivity, the reciprocal of electrical conductivity, affects nearly all induction heating system parameters including depth of heating (current penetration depth), heat uniformity, coil electrical efficiency, coil impedance (load matching capability) and others. Electrical resistivity varies with temperature, chemical composition, metal microstructure and grain size. It increases nonlinearly with temperature for steels and cast irons.

Relative magnetic permeability (μ_r) is a nondimensional parameter that indicates

the ability of a material to conduct the magnetic flux better than vacuum or air. It has a marked effect on all basic induction phenomena including the skin effect, end effect and proximity effect, and also has a major effect on coil electrical parameters [1]. The magnetic permeability of a particular metal is a function of both temperature and magnetic field intensity.

Electrical resistivity and magnetic permeability are strongly dependent on the chemical composition (Figs. 9, 10 and 11).
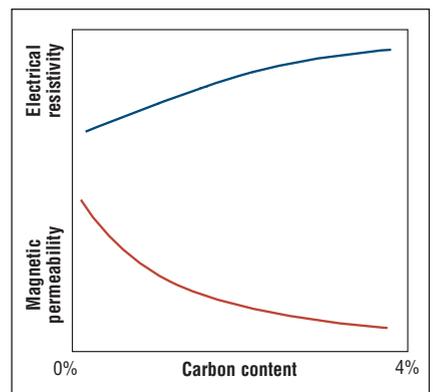

Fig. 9. Influence of carbon content on electrical resistivity and magnetic permeability of carbon steels and cast irons at ambient temperature
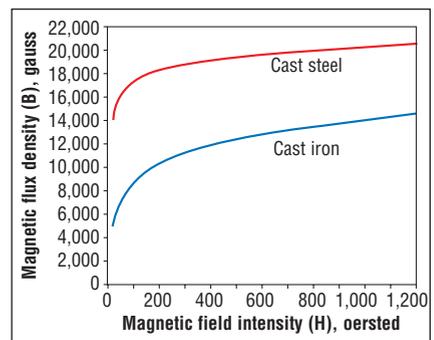

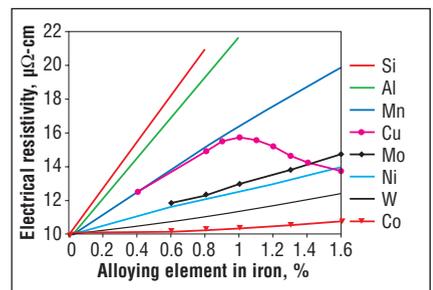**Fig. 10. Magnetization B-H curves for cast steel and cast iron [13]**

Fig. 11. Influence of small amounts of alloying elements on the electrical resistivity of iron [14]

Property	Change	Influence on induction heat treatment process
Thermal conductivity	Decrease	Less soaking action from the high temperature areas towards low temperature regions. Greater temperature gradients and stresses during heating and quenching. Slower cooling of workpiece internal areas and core during quenching. Shorter transition area.
Electrical resistivity	Increase	Greater depth of heating and larger current penetration depth. Increase of the coil electrical efficiency produces higher temperatures while utilizing the same energy/power.
Magnetic permeability	Decrease	Greater depth of heating, larger current penetration depth and lower coil electrical efficiency. Coil power factor reduction. Smaller thermal gradients and stresses during heating.

Fig. 8 Effects of material physical properties on induction heating behavior

Cast irons have higher electrical resistivity but lower magnetic properties compared with carbon steels. Thus, a coil using the same power supply and frequency has a different heating effect on carbon steel, alloy steel or cast iron parts of the same geometry [1].

A material's thermal properties also are a function of chemical composition. Since the cycle time of induction heating is much shorter than those of alternative heating processes, the variation in thermal conductivity of the heated material has a greater effect on transient and final thermal conditions of the inductively heated parts.

Thermal conductivity of cast irons is typically lower than that of carbon steels resulting in much weaker "soaking" action during surface hardening or selective hardening. Therefore, in contrast to surface hardening of steels, self-quenching is practically never used in hardening cast irons. For example, in the case hardening of gray iron cyclinder liners in Fig. 6, self-quenching was not applied even for the required shallow case depth of 0.8 mm (0.03 in.). It is important to remember that the size, shape, dispersion and amount of graphite flakes affect not only the mechanical properties, but also the electrical, magnetic and thermal properties of gray cast irons [1].

When discussing induction surface hardening of steel, the phenonmenon of super hardening is often mentioned [1,4], wherein the surface hardness of an induction hardened steel could be 2-3 HRC higher than that for through-heated, furnace-hardened steel [1,4]. This phenomenon is particularly noticeable in induction hardened steels having a 0.35-0.6% carbon content. Super hardening has never been observed in induction hardening iron castings.

Conclusion

The material discussed in Part 1 and Part 2 of this article is representative of metallurgical "fine points" and subtleties that sometimes are incorrectly assumed or improperly used in the application of induction hardening.. However, there many other principles of heat treatment that must be carefully thought out when applying them to the induction hardening compared with alternative heat treating methods to prevent unanticipated surprises. **IH**

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Additional related information may be found by searching for these (and other) key words/terms via BNP Media LINX at www.industrialheating.com: induction hardening, surface hardening, selective hardening, induction heating, CCT diagram, self quench, mass quench, martensite transformation, retained austenite, cryogenic treatment, homogeneous austenite, hardenability, Jominy-end quench, Grossmann's test, cast iron, carbon equivalent (CE), electromagnetic properties, electrical resistivity, magnetic permeability, super hardening.