Selected aspects of hardening iron castings by induction are presented. Topics include processing gray and ductile irons, the roles of composition and prior microstructure in heat treatability, prevention of cracking, and the age strengthening effect.

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This article focuses on some subtle aspects of induction hardening of cast irons. Much of the information presented was adapted from the recently published *Handbook of Induction Heating*. A common application of induction heat treatment is the hardening of cast iron auto parts (camshafts, crankshafts, cylinder liners, gears, rollers, and rocker arms, for example) to improve their strength, wear resistance, and/or other mechanical properties. The ductile (nodular) iron crankshaft shown in Fig. 1 has been induction hardened using Inductoheat’s SHarP-C process.

It is important to remember that the term “cast iron” does not signify a single material, but rather a large family of alloys that populate the right side of the Fe-Fe₃C phase transformation diagram. They are distinguished by a high carbon content (2% C and up) and a wide range of properties. Cast irons that are frequently induction hardened include gray irons, ductile (nodular) irons, and, to a lesser extent, malleable and compacted graphite irons.

**Cast iron hardening basics**

In any discussion of the heat treatment of cast irons it is important to understand the concept of carbon equivalence (CE). The CE establishes the relationship between the effects of alloying elements in an iron and the amount of carbon that would be required to provide a similar heat treatment effect. Several expressions have been developed for calculating CE. The one defined in Ref. 3 is often used at Inductoheat:

\[
CE = \%C + 0.3(\%Si) + 0.33(\%P) - 0.07(\%Mn) + 0.4(\%S)
\]

where \%C is the value of the total carbon content (TC). In general, the lower the CE the better the cast iron’s response to induction hardening.

A typical heat treatment for hardening of both steels and cast irons in-

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*Fig. 1 — An induction hardened ductile (nodular) iron crankshaft. Also shown are the hardness pattern, and microstructures of the surface, hardened case, transition zone, and “green” core at a connecting rod bearing journal. Required case depth: 1.8 mm (0.07 in.). Etched with nitral.*

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the eutectoid and eutectic reactions on the Fe-C-Si diagram occur at higher temperatures and over a range of temperatures that increases with an increase of both carbon content and silicon content. The temperature range of 860 to 960°C (1580 to 1760°F) is typical for induction surface hardening of gray and ductile iron castings.

Induction surface hardened iron castings usually have a well-defined case depth with a relatively shallow transition zone. Besides carbon and silicon, all commercial cast irons also have other intentionally added alloying elements and residual impurities that might affect critical temperatures. The possible variation of critical temperatures should be kept in mind when choosing hardening parameters.

Note: Required temperature ranges for induction hardening of plain carbon steels depend on the carbon content, heat intensity, and prior microstructure. In general, the lower the carbon content, the higher the hardening temperature. Typical ranges: annealed prior microstructure, 870 to 1100°C (1600 to 2010°F); normalized, 840 to 1000°C (1545 to 1830°F); quenched and tempered, 820 to 930°C (1510 to 1705°F).

System design: The first step in designing an induction surface hardening process is to specify the required surface hardness and hardness profile, the case depth, and the depth of the transition zone. The hardness distribution along the workpiece radius/thickness — the hardness profile — depends on the temperature distribution, quenching conditions, and the prior microstructure, chemical composition, grain size, and hardenability of the metal being heat treated.

Temperature distribution in induction surface hardening is controlled by specifying the frequency, time, power density, and workpiece/coil geometry. Depending on heat treat requirements and part geometry, the hardening system can range from a relatively simple apparatus to a sophisticated, complex machine. Examples of the latter are shown in Fig. 2: compact induction hardening and tempering machines for heat treating cast iron camshafts. The machines were built to stringent automotive specifications.

Hardening of gray iron

Gray cast iron consists of carbon in the form of flake graphite in an iron
matrix (Fig. 3). The combination of high carbon content and brittle graphite flakes makes gray iron castings hard and brittle. They have a low tensile strength and a poor ability to withstand shock loading and thermal shock.

The ability of a gray iron part to be hardened depends on the type of matrix (ferritic, ferritic-pearlitic, or pearlitic) and the amount, size, shape, and distribution of the graphite flakes. A pearlitic matrix provides a better response to induction heat treating. The graphite flakes should be fine, uniformly distributed, and randomly oriented (Type A fine graphite). The surface hardness achievable by induction hardening is reduced as the amount of graphite increases.

Gray cast irons having a ferritic matrix are not very suitable for induction hardening.

Crack prevention: Gray iron's brittleness may pose certain challenges to induction heat treaters, due to a tendency to crack during rapid heat-up or severe cooling. Preheating and “soft” (low-intensity) quenching are often used to reduce thermal stresses and shocks. On the other hand, there have been cases where gray irons have been successfully hardened using a short heat-up time (less than 3 seconds) and a quench in plant water.

Figure 4 shows a unitized machine for induction processing of gray iron cylinder liners for commercial vehicle engines. It combines two independently operated heat stations for hardening and tempering. High-speed, servo-driven scanning assemblies and optimized process parameters allow very short heating times and production rates as high as 50 liners per hour.

Remember that the size, shape, dispersion, and amount of graphite flakes affect not only mechanical properties, but also electrical, magnetic, and thermal properties of gray iron castings. The effects of changes to these properties should be considered when developing an induction hardening process.

Hardening of ductile irons

In contrast to gray irons, ductile or nodular irons contain carbon particles in the form of graphite nodules (Fig. 1) instead of flakes (Fig. 3). The nodules serve as “crack arresters,” and give ductile irons important advantages over gray irons, including ductility, relatively high tensile strength and bending strength, and moderate elongation.

Ductile iron, like cast iron in general, represents a large group of materials offering a wide range of properties. There are five ductile iron subgroups: ferritic, pearlitic-ferritic, pearlitic, martensitic, and austempered ductile irons. Induction hardening is usually applied to the martensitic, pearlitic, and, to a lesser extent, pearlitic-ferritic grades. Martensitic ductile irons require the lowest hardening temperatures and shortest heat-up times, and produce well-defined, crisp case hardness patterns.

Because ductile irons are inherently strong, they can handle much greater stresses during heating and quenching without cracking than gray irons. Note, however, that although the graphite nodules serve as crack arresters, they provide no guarantee that a casting will not crack during intensive heating and/or severe quenching. Caution, common sense, and experience should be exercised when choosing parameters for induction surface hardening of ductile iron, particularly if it has a high phosphorus content. (High phosphorus can cause excessive brittleness. Typically specified maximum contents are 0.12% P for gray irons and 0.04% P for ductile irons.)

Age strengthening cast irons

Heat treaters with extensive experience in induction hardening cast iron may have sometimes noticed that seemingly identical cast iron parts—parts having the same chemical composition, geometry, grain size, and microstructure, produced at the same foundry, and even coming from the same lot or batch—have different responses to surface hardening. Under identical heating and quenching conditions, some castings may process very easily, while others may have substantial cracking. One reason for this behavior is a phenomenon called “age strengthening.”

In the first systematic experimental study of this phenomenon, Nicola and Richards report that aging at room temperature for about 60 days can strengthen gray cast irons by up to 12%. Approximately 87% of the cast irons evaluated revealed the effect. The tensile strength-to-hardness ratio also increases because the Brinell hardness does not change with time.

Age strengthening occurs in both
cupola and induction melted irons. Interstitial (free) nitrogen appears to be a controlling factor in determining whether aging will take place. Therefore, age-strengthened castings would be less likely to crack when exposed to thermal gradients during heating and quenching. This may also explain the traditional foundry practice in the past of storing some castings — gray iron parts in particular — for several months before heat treating them.

Therefore, to ensure the reliability of a cast iron hardening process, it is important to conduct a run-off using relatively new or fresh parts.

**Favorable** metal conditions

It is very important to have “favorable” metal conditions prior to induction hardening. Part design, casting quality, process parameters, and prior microstructure are among the factors to be considered.

**Design factors:** A complex part geometry and the presence of holes and/or sharp corners, for example, can affect the success of an induction hardening operation. The surface condition of the part also is important. voids, microcracks, notches, and other surface and subsurface discontinuities, as well as stress concentrators such as sharp corners and grooves can lead to crack initiation during hardening. As the cast iron experiences the expansion-contraction cycle, thermal gradients and stresses can reach critical values, opening notches and microcracks. Conversely, a homogeneous metal structure having a smooth surface free of voids, porous regions, microcracks, and notches is less likely to crack during heat treatment.

Alternating electrical currents of medium and high frequency tend to overheat sharp corners. Sharp corners also tend to cool faster than the rest of the casting during quenching. Therefore, if possible, corners should be generously rounded and chamfered for optimum results in both heating and quenching.

Complex-shaped parts can pose challenges in obtaining the required hardness pattern. During heating, thicker sections may not reach the required temperature as fast as thinner sections. Coil profiling and special process settings may help.

Large variations in section thickness also can create difficulties during quenching, due to differences in cooling behavior between thinner and more massive regions of the part. Adjustments to inductor design and quench spray blocks should be made.

**Process parameters:** Important process parameters include frequency, power density, heat-up time, spray quenching specifics, and inductor design. Modern induction hardening machines boast the ability to monitor and control significant process variables. A control system should allow presetting key input parameters with the expectation that the required outputs will result (via a specified control algorithm).

The monitoring system must be independent of the control system, and should provide the operator with information about what is actually happening. It should indicate whether the measured values of a parameter are essentially the same as those recorded for a test piece known to have been properly processed. If the values are the same or within acceptable limits, it may be inferred that the production iron casting has been successfully processed.

**Troubleshooting:** The task of successfully surface hardening cast irons will be simplified if the following conditions are satisfied: correct chemical composition, “friendly” prior microstructure, correct process recipe, and design factors and casting quality. Details follow.

**Alloying and residual elements**

The heat treat must have a clear picture of the chemical composition of the cast iron being processed. If the casting does not respond to heat treatment in the expected way, the first step in determining the reason why is to ensure that the iron has the proper chemical composition. Although carbon and silicon are principle alloying elements of gray, malleable, compacted graphite, and ductile irons, and have the most significant influence on the microstructure of hardened material, the heat treat must also check for the presence and amounts of other elements.

Commercial cast irons contain a host of other alloying elements in amounts ranging from insignificant to substantial, including manganese, chromium, nickel, copper, molybdenum, phosphorus, and sulfur. In addition, cast irons also contain residual impurities that can, under certain conditions, act as alloying elements and markedly affect the material’s response to induction hardening, resulting in changes to the critical temperature on the phase transformation diagram and shifts in continuous cooling curves.

Composition factors may cause a noticeable variation in the microstructure of surface hardened castings. For example, even a very small amount of an element such as bismuth, lead, titanium, tin, or nitrogen may have a marked effect on the microstructure of the hardened part. It also has been reported that excessive phosphorus can make iron castings more brittle. (The amount of phosphorus normally specified is less than 0.12% for gray irons and 0.04% for ductile irons.)

In addition, the same type of cast iron purchased from different suppliers can have appreciably different properties. Casting process variables such as the solidification rate and amount of residual elements may cause those differences. Special attention should be paid to elements that promote graphitization, and to combinations of elements, such carbon and silicon, and sulfur and manganese, that may have a synergistic effect. It is also important that close control be maintained over the CE (carbon equivalent) and TC (total carbon) values.

**Impact of prior microstructure**

Austenite must contain enough carbon to form the required amount of martensite upon quenching. This is why it is preferable that cast irons have a homogeneous quenched and tempered or fully pearlitic (consisting entirely of fine pearlite) microstructure prior to induction hardening.

Ferritic irons are not well suited for hardening by induction, because carbon has a low solubility in ferrite. Therefore, the only way for carbon to enter the austenite matrix is by diffusion from eutectic graphite flakes or nodules. This requires a long time, eliminating a major advantages of induction hardening; the short heat time. Note, however, that most hardened iron castings will contain some ferrite. The amount should not exceed ~8 to 9%, or reduced hardness and increased scatter in hardness readings can result.

Other “unfriendly” prior microstructures include those having alloy segregation or large clusters of graphite. When located near a gray iron casting’s surface, large graphite flakes or clusters of flakes having a preferred orientation serve as stress raisers (Fig. 5), making the casting
more susceptible to crack development during rapid heating (particularly at frequencies of 30 kHz and higher) and severe cooling (particularly water quenching). When hardened, these irons also may develop soft spots where the large clusters are located.

Also to be avoided are eutectic carbides, caused by insufficient time at austenitizing temperature, that can encourage cracking in all types of cast irons suitable for induction hardening. The propensity for cracking derives from the complex stress distribution created during quenching due to significant differences in the physical properties (thermal expansion coefficient and density, for example) of carbides and martensite.

Other potentially crack-prone structures include dendritic structures, and the undercooled graphite structure that results from rapid solidification and insufficient inoculation.

**Importance of process recipe**

The proper recipe for the induction heat treating process includes an appropriate austenitizing temperature and time, which are functions of the cast iron grade and specifics of the heating and quenching portions of the cycle. The austenitizing temperature should be sufficiently high and the austenitizing time sufficiently long to ensure that all required diffusion-type processes are completed, so that the martensitic structure formed during quenching will contain no “ghost pearlite” or an excessive amount of “free ferrite.” This will avoid formation of a complex martensitic-pearlitic structure containing unacceptably large islands of “free ferrite,” a structure characterized by low hardness, large scatter in hardness values, and a pronounced tendency to develop cracks.

There are several ways to estimate the austenitizing temperature required for induction hardening cast irons. For example, Inductoheat often uses the following expressions to estimate the minimum austenitizing temperature for unalloyed cast irons heated at a moderate rate:

- Austenitizing temperature, °C = 800 + 28(%)Si + 25(%)Mn
- Austenitizing temperature, °F = 1472 + 50(%)Si + 45(%)Mn

**Overheating**: There also is a maximum austenitizing temperature that should never be exceeded. Due to the nonequilibrium nature of induction heating, all critical temperatures on equilibrium phase transformation diagrams are shifted to higher temperatures. Therefore, when hardening cast irons at sufficiently high heating rates — 50°C/s (90°F/s) and higher — to ensure the completion of the transformation to austenite, the required temperature of the metal may approach a dangerously high level. Overheating a cast iron results in decarburization of the surface and excessive retained austenite in the as-quenched microstructure. Hardness is often reduced. Overheating also can lead to grain growth and the formation of coarse martensite and, possibly, undesirable “white iron” structures. Cracking is another possibility that accompanies the high temperatures, due to the large thermal gradients produced during heating and, especially, quenching.

The phase transformation diagrams show that the cast iron eutectic starts to melt at a temperature about 150 to 250°C (270 to 450°F) lower than that for most of the wrought carbon steels used for induction hardening. For example, in the case of moderate heat intensity, the cast iron eutectic begins to melt at ~1150°C (2090°F). If this temperature is inadvertently exceeded, there is a pronounced possibility of surface melting, incipient melting, or grain boundary liquation. The situation becomes more complicated if low-melting-temperature elements have been added to the iron. Copper or tin, for example, often are added to gray and ductile irons to promote pearlite formation.

These considerations point up the need for precise monitoring and reliable control systems when hardening cast irons. A reliable temperature control system is even more important for hardening iron castings than it is for surface hardening of wrought steels. Precision monitoring is particularly critical when induction scan hardening of cast irons having a high silicon content and large amounts of certain alloying elements. Monitoring and control principles, and the systems in use today are discussed in detail in Ref. 1.

**Quench cracking**: Since cast iron, and gray irons in particular, are much more susceptible to cracking upon quenching than wrought steels, a preheat or slow heating during the initial stage of the process — from ambient temperature to about 600°C (1100°F) — and “mild” quenching often are
used. This reduces thermal shocks and allows time for thermal stresses to relax. Media used to minimize distortion and the possibility of cracking during quenching of gray iron include oil at 80 to 100°C (175 to 210°F) and concentrated polymers.

Of course, numerous cases also can be cited where gray iron castings have been successfully hardened using a short heating time (less than 3 seconds) and a water quench. Use of water requires an appropriate prior microstructure and the correct combination of process parameters (including scan rate, pressure, flow rate, water temperature, and quench block design).

**Design factors, casting quality**

Poor-quality castings may not properly induction harden. Casting defects, which can cause problems by themselves, also may hinder the hardening process. Porosity, inclusions, sand and gas defects, blowholes, and dimensional errors within the hardened case may cause localized redistribution of eddy currents induced within the heated part by the induction coil, resulting in, for example, overheating, burning, cracking, and scatter in hardness data.

For iron castings of complex shape, with a nonuniform geometry and a combination of thick and thin sections, regions of different mass will tend to respond differently to heating. This promotes the formation of thermal gradients and thermal stresses, which, in turn, create conditions favorable to distortion and crack initiation, particularly at transitions between regions of significantly different mass.

The situation can be complicated when these “transitional” thermal stresses combine with residual stresses developed during previous manufacturing operations (casting, machining, honing, grinding, and peening, for example). Long castings having thin, complex cross-sections are more likely to have residual stresses than a typical massive, blocky casting. To reduce the probability of cracking during induction hardening, a stress relief prior to heating can often be advised. See Ref. 1 for more information about stress formation during induction heat treating, and for details on tempering and stress relieving of hardened parts. [HIT]

**References**


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