

Metallurgical 'Fine Points' of Induction Hardening

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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.

Hardening of steels and cast irons represents the most popular application of induction heat treatment (Fig. 1). Induction hardening is a complex combination of electromagnetic, heat transfer, and metallurgical phenomena [1]. Due to the physics of electromagnetic induction, heating can be localized to areas where metallurgical changes are desired. The three most common forms of induction hardening are surface hardening, through hardening, and selective hardening. Depending on the specific application, selective hardening is sometimes considered a part of surface hardening or through hardening.

The first step in designing an induction-hardening machine is to specify the required hardness pattern including surface hardness, case depth and transition zone. Temperature

distribution in induction surface hardening is controlled by selection of frequency, time, power and workpiece/coil geometry [1].

Hardening of steels and cast iron components may be done for the purpose of obtaining certain properties including, but not limited to, strength, fatigue and wear resistance. The traditional description of the steel hardening procedure involves heating the entire component, or a part of the component that needs to be hardened, to the austenitizing temperature, holding it if necessary for a period long enough to achieve complete transformation to austenite, and then rapidly cooling it below the martensite start (M_s) temperature, where martensite transformation begins.

For example, Fig. 2 shows the dynamics of the induction heating of a carbon steel cylinder and its cooling during quenching

for surface hardening. After 4.1 seconds of heating, the surface layer reaches a final temperature of approximately 1050°C (1920°F). The core temperature does not rise significantly due to several factors, such as an electromagnetic skin effect and relatively short heating time. Because of these factors, the heat soak from the surface toward the core is not sufficient to equalize temperature along the radius.

After the heating stage is completed, the quenching stage begins. The high temperature of the workpiece surface layer begins to decrease in the first stage of quenching. Figure 2 shows that after 2 seconds of quenching, the surface temperature is reduced by as much as 450°C (810°F), resulting in a workpiece surface temperature of 600°C (1110°F). At this point, the maximum temperature is located at a distance of 3 mm (0.120 in.) below the surface. After 5 seconds of quenching, the surface temperature decreases almost to the temperature of



Fig. 1. Dual shaft induction scanner

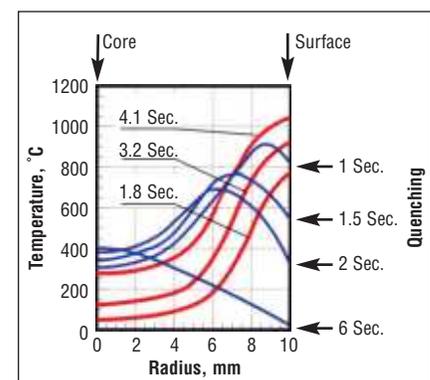


Fig. 2. Dynamics of induction heating of a carbon steel cylinder (20 mm OD) and its cooling during quenching ($F = 40$ kHz) [1]; red is heating and blue is cooling.

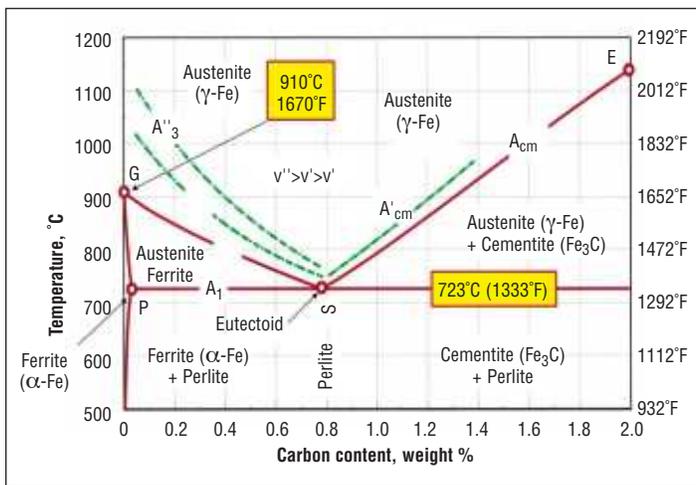


Fig. 3. Lower left portion of the iron-iron carbide equilibrium phase transformation diagram

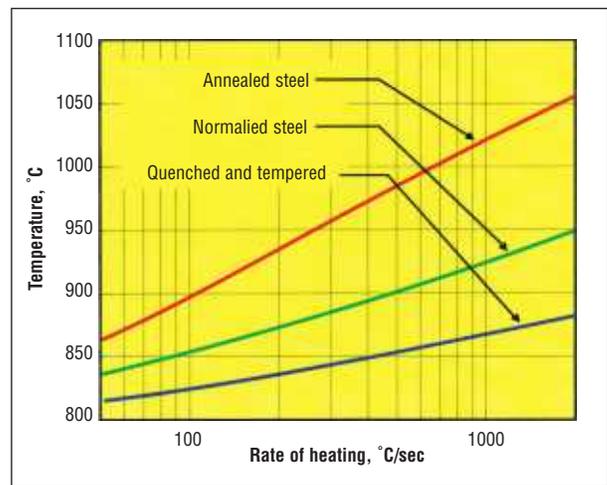


Fig. 4. Effect of initial microstructure and heating rate on A3 critical temperature for AISI type 1042 steel [3,4]

the quenchant, while the core still remains quite warm at a temperature above 400°C (750°F).

In some cases, heat treaters do not cool the part completely, and after unloading the part from the induction coil, it is kept for some time on the shop floor. During that time, the heat of the warm core travels toward the surface, eventually resulting in a uniform temperature distribution within the part. In this case, the remaining heat is used for a slight temper back (self-tempering), which imparts some ductility to the part.

At first glance, this operation is very straightforward. However, in many cases, certain metallurgical phenomena and principles of heat treatment frequently 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. Following are some examples that illustrate this.

Can you directly apply the iron-iron carbide (Fe-Fe₃C) equilibrium phase-transformation diagram to induction hardening of steel?

When iron is alloyed with a different percent of carbon, the critical temperatures often are determined based on the Fe-Fe₃C diagram. Figure 3 shows the lower left-hand part of this diagram representing the heat treatment of steels. This widely used diagram represents a graph of temperature versus carbon content of the steel and shows

the effect of heating the metal to elevated temperatures or metal cooling that causes a transformation in its crystalline structure. It is also used to determine the range of temperatures in which certain types of heat treatment of the steel may be carried out. Often, heat treat practitioners use this diagram to determine hardening temperatures.

However, it is important to be aware that this diagram might be misleading in majority of induction hardening applications because it is valid only for the equilibrium condition of plain carbon steel at a pressure of one atmosphere. The existence of non-equilibrium conditions, appreciable amounts of alloying elements, pressure other than atmospheric and certain prior treatment can significantly shift the critical temperatures.

One of the major requirements of an equilibrium condition is sufficiently slow heating. Ideally, for sufficiently slow heating/cooling, transformation temperatures should be approximately the same in heating as well as in cooling resulting in no appreciable difference between the A_c and A_t critical temperatures. However, from a practical standpoint, the equilibrium condition simply does not exist in induction hardening.

The A_c temperatures are always higher than A_t temperatures. The difference between A_c and A_t temperatures represents a thermal hysteresis, which is a function of several factors including the metal chemical

composition and the heating/cooling rate. The greater the rate of heating/cooling, the greater will be the difference between the A_c and A_t temperatures.

Induction hardening is a very fast process. Heat intensity often exceeds a magnitude of 100°C/sec (180°F/sec), and in some cases reaches 900°C/sec (1620°F/sec) and even higher. Therefore, the process of phase transformation cannot be considered as equilibrium, and the phenomenon of thermal hysteresis is always pronounced.

Fast heating drastically affects the kinetics of the austenite formation, shifting it toward higher temperatures to create sufficient conditions for the required diffusion-based processes [2]. Figure 4 shows the effect of the heating rate on the A_{c3} critical temperatures of steel [3, 4]. The inability of the classical Fe-Fe₃C diagram to take into consideration heating intensity noticeably limits its use to predict required temperatures in induction hardening applications.

The microstructure of steel prior to heat treatment (sometimes referred to as initial structure, structure of the parent material, and structure of the “green” part) also has a pronounced effect on the results of the heat treatment and required process parameters. This includes, but is not limited to, the austenitizing temperature and the time required to hold at that temperature.

As can be seen from Fig. 4, even for induction hardening of AISI 1042 plain carbon steel, depending on the heat intensity

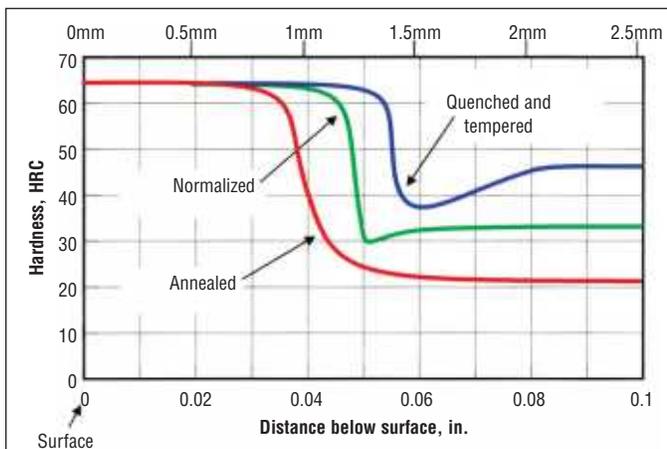


Fig. 5. Effect of initial microstructure in AISI type 1070 steel bars on response to surface hardening using 450-kHz induction generator operated at a power density of 2.5 kW/cm² (16 kW/in.²) [5]

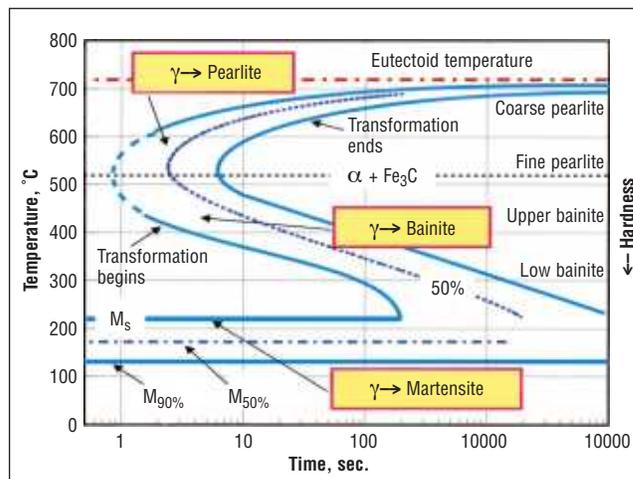


Fig. 6. Time-temperature isothermal transformation diagram for AISI type 1020 plain carbon steel, austenitized at 900°C; grain size: 6 [3,7]

and structure prior to induction hardening, the required hardening temperatures range from 1620 to 2000°F (880 to 1095°C) for annealed prior microstructures, 1550 to 1830°F (840 to 1000°C) for normalized prior microstructures and 1510 to 1710°F (820 to 930°C) for quenched and tempered microstructures.

A quenched and tempered microstructure is the most favorable prior microstructure [1] followed by a normalized structure consisting of fine pearlite, which provides rapid transformation allowing one to reduce the required temperature for austenite formation. This results in fast and consistent metal response to induction hardening with a minimum amount of grain growth, the smallest shape/size distortion, surface oxidation, minimum required heating energy and well-defined (crisp) hardness pattern with a short transition zone (Fig. 5). This type of initial structure can also result in higher hardness and deeper hardened case depth compared with other structures.

An initial steel microstructure containing a significant amount of coarse pearlite and, most importantly, coarse ferrite or clusters or bands of ferrite, is considered to have an unfavorable structure. Ferrite is practically a pure iron and contains an insufficient amount (less than 0.025%) of carbon required for the martensite transformation. Large areas (clusters or bands) of ferrite require a long time for carbon to be able to diffuse into the carbon-poor area of

the ferrite. The ferrite clusters or bands can function as one large ferrite grain and often will be retained in the austenite upon fast heat up [1]. After quenching, a complex ferritic-martensitic microstructure can be formed. Scattered soft and hard spots and poor mechanical properties characterize this structure. Appreciably higher temperatures and longer heat times are required to austenitize those structures. It is strongly recommended to avoid the segregated and banded initial microstructures of “green” parts.

Steels containing large stable carbides (i.e., spheroidized microstructures) also have poor response to induction hardening, and require prolonged heating and higher temperatures to complete austenitization. Longer heating time leads to grain growth, the appearance of coarse martensite formation, an extended transition zone, surface oxidation/decarburization and increased shape distortion. Coarse martensite has a negative effect on such important properties as toughness, impact strength and bending fatigue strength, and is susceptible to cracking.

Thus, when determining the appropriate induction hardening temperatures for a carbon steel component, it is imperative to remember the limitations of the equilibrium Fe-Fe₃C phase transformation diagram and to take into account the specifics of the process including the heat intensity and microstructure of the green part.

Can time-temperature-transformation (TTT) and continuous-cooling-transformation (CCT) diagrams be directly applied in induction hardening?

TTT and CCT diagrams are widely used in the heat treat industry to determine the end products of austenite transformation when steel is cooled below the A₁ critical temperature (Figs. 6 and 7). The nomenclature used on these diagrams to represent a particular structure is: A = austenite, F = ferrite, P = pearlite, B = bainite and M = martensite. Double letters are sometimes used to emphasize a certain feature of a particular structure. For example, CP = coarse pearlite, FP = fine pearlite, UB = upper bainite and LB = lower bainite.

Time is plotted on the x axis (a logarithmic scale) versus temperature on the y axis (Fig. 6). A distinguishing feature of TTT diagrams is the presence of two S-shaped curves (sometimes referred to as C-shaped curves). The left solid curve represents the beginning (the start) of the transformation process and the right solid curve designates the end of the isothermal transformation. Often TTT diagrams show a curve between the transformation start and end curves that represents the completion of 50% of the transformation of the austenite. Because there is no representation of carbon content or combination of alloying elements for the steel under consideration, a different chart is required for each chemical composition to be analyzed.

CCT diagrams allow prediction of the final microstructure of the steel taking into account the continuous nature of the process during cooling of austenite. CCT diagrams are typically slightly shifted to lower temperatures and longer times compared with TTT diagrams. Although TTT (isothermal transformation) and CCT diagrams are helpful, it is important to remember that there are several limitations when trying to apply the diagrams to induction hardening.

Both TTT and the CCT diagrams were developed assuming homogeneous austenite, which is not always the case in induction hardening. Inhomogeneous austenite means there is a nonuniform distribution of carbon. Therefore, cooling of high and low carbon concentration areas of inhomogeneous austenite would be represented by different CCT curves having different critical cooling curves. TTT diagrams assume an isothermal process where the steel component upon cooling is held at a fixed temperature below the A1 critical temperature, which is never the case in induction hardening. While CCT diagrams take into consideration continuous cooling during quenching, the cooling curve assumes a constant cooling rate, which is often not a valid assumption, particularly in induction scan hardening applications.

In addition the samples used to develop these diagrams had small cross sections. Therefore, there will be some inherent errors in trying to apply the curves to moderate or large sized components, as well as complex-shaped parts. Components having a different surface area-to-volume ratio have different cooling characteristics.

In induction hardening, the heat exchange process between the surface of the heated component and the quenchant is a function, among other factors, of the surface temperature, which is not constant. In addition, the workpiece temperature (austenitizing temperature) prior to applying quenchant is typically not the same as assumed in the CCT diagrams. In addition, the temperature distribution prior to quenching is nonuniform. The existence of a cold core that functions as a heat sink has a marked effect on the severity of the cooling rate

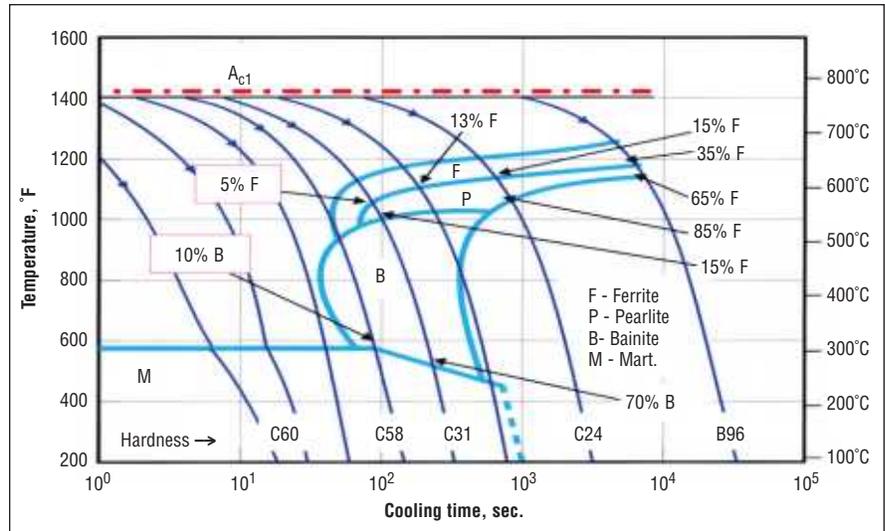


Fig. 7. Continuous cooling transformation (CCT) diagram for AISI type 15B41 steel (0.42%C, 1.61% Mn, 0.29% Si, 0.006% P, 0.019% S, 0.004% B), grain size: 7-8 [8]

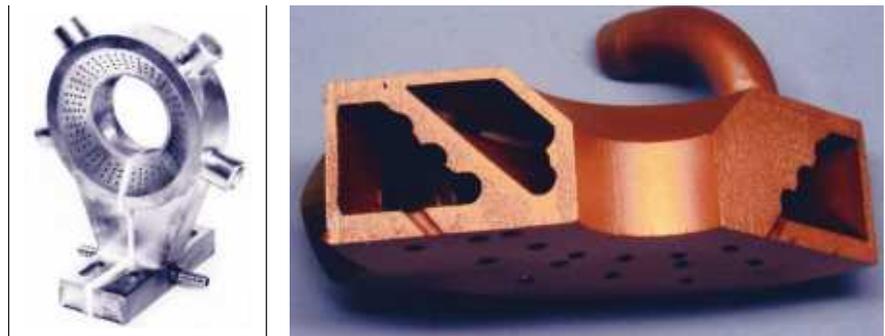


Fig. 8. Typical machined scanning inductor with integral quench (left) and cross section of a single turn scan coil showing quench chamber and coil cooling chamber (right)

during quenching.

Therefore, while TTT and CCT diagrams are useful in helping the heat treater to understand the basic phenomena and principles of heat treatment, it is important to be aware of its inherent limitations when applying to induction hardening.

Are there any peculiarities in quenching techniques used in induction hardening?

Spray quenching is typically used in induction hardening applications. Spray quenching works best if the component is rotated during the quenching operation, which ensures uniformity in quenching. By rotating symmetrical parts, the workpiece simulates a constant impingement rather

than many small impingements. The quench holes are typically placed facing the heated component at 0.1875 to 0.250 in. (~5 to 6 mm) intervals and have a staggered pattern. The orifice size is related to the specifics of quenching requirements including coil-to-workpiece geometry, air gap between the quench block and the workpiece surface, quench concentration and required flow, etc. In some cases, the quench is built into the coil (Fig. 8), while a barrel or quench block is separate from the coil in other cases.

The intensity of spray quenching depends on the flow rate; the angle at which the quenchant strikes the workpiece surface; and temperature, purity and type of quenchant. Different types of quenchants

used include water, polymer-based media and, to lesser extent, oil and forced air.

The classical cooling curves widely published in the literature representing three stages of quenching; that is, the vapor blanket (A-stage), nucleate boiling (B-stage) and convective cooling (C-stage), cannot be applied directly with spray quenching. Due to the nature of spray quenching, the first two stages are greatly suppressed in time. At the same time, cooling during the convection stage is more intense with spray quenching plus rotation of the component than represented by classical cooling curves.

The differences are of both a quantitative and qualitative nature. This includes, but is not limited to, specifics of film formation and heat transfer through the vapor blanket during the initial stage of quenching, as well as kinetics of formation, growth and removal of bubbles from the surface of the heated component during the nucleate boiling stage [7]. The film thickness of the vapor blanket during the A-stage of quenching is typically much thinner with spray quenching than that obtained with quenching in a tank, and depends on flow rate, impingement angle and other characteristics of a spray quenching system.

Transition between the A-stage and B-stage of quenching is smoother with spray quenching than shown on classical cooling curves for quenching in the tank. During nucleate boiling, bubbles are a smaller size because they do not have sufficient time to grow. Much larger numbers of bubbles are formed during spray quenching and the intensity with which they remove heat from the surface of the component is substantially greater compared with bulk (tank) quenching. This is one of the most important factors responsible for more intensive quench severity of spray quenching.

In some surface hardening applications requiring shallower case depths, self-quenching is used. In some cases, the effect of thermal conduction away from the surface by the cold core provides sufficient cooling to miss the nose of the continuous cooling curve. This self-quenching technique (also known as mass quenching) allows the elimination of using liquid quenchants to achieve a shallow case. **IH**

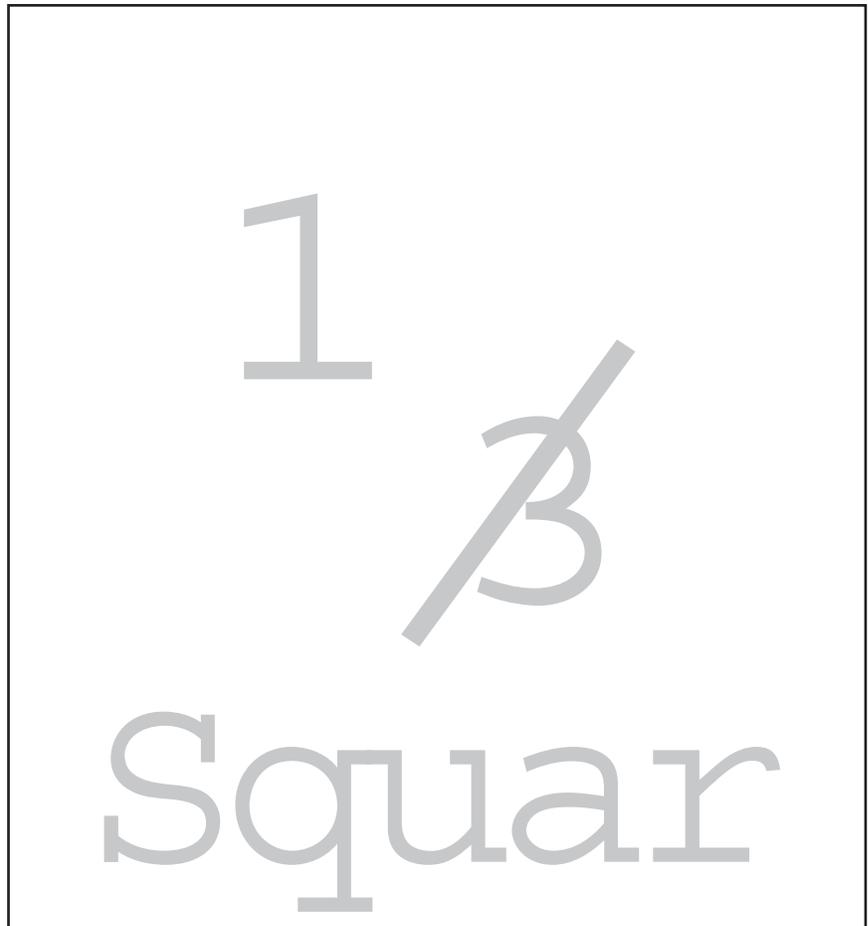
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Additional fine points of induction heating treating will be discussed in Part 2 of this article in the May 2005 issue of IH.

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