

# PROFESSOR INDUCTION

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Professor Induction welcomes comments, questions, and suggestions for future columns. Since 1993, Dr. Rudnev has been on the staff of Inductoheat Group, where he currently serves as group director — science and technology.



In the past, he was an associate professor at several universities. His expertise is in materials science, metallurgy, heat treating, applied electromagnetics, computer modeling, and process development. Dr. Rudnev is a member of the editorial boards of several journals, including *Microstructure and Materials Properties* and *Materials and Product Technology*. He has 28 years of experience in induction heating. Credits include 16 patents and 128 scientific and engineering publications.

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## Metallurgical insights for induction heat treaters

### PART 1: INDUCTION HARDENING TEMPERATURES

This is the first part of a new series that will alternate with “Systematic analysis of induction coil failures.” There have been 10 installments in the coil failures series. Part 11 will be published in the July Heat Treating Progress. It will focus on failure modes of induction coils used for heating internal surfaces (ID inductors).

**H**ardening of steels and cast irons represents the most popular application of induction heat treatment. The three most common forms of induction hardening are surface hardening, through hardening, and selective hardening.<sup>1</sup>

Steel hardening is conventionally described as involving heating the entire component, or a part of it, to the austenitizing temperature, holding it if necessary for a period long enough to obtain a complete transformation to homogeneous austenite, and then rapidly cooling it to below the  $M_s$  temperature where the martensitic transformation begins.

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

ness pattern is directly related to temperature distribution and is controlled by selection of frequency, time, power, and workpiece/coil geometry.

When iron is alloyed with different percentages of carbon, the critical temperatures are often determined by the iron-iron carbide phase transformation diagram (Fe-Fe<sub>3</sub>C diagram). The lower left portion of this diagram represents heat treating of steels, and is shown in Fig. 1.

This widely used diagram is a graph of temperature versus the carbon content of the steel and shows how heating to elevated temperatures or cooling from an elevated temperature can cause a transformation in the steel’s crystal structure.

**Induction’s different:** However, it is important to be aware that this phase diagram might be misleading

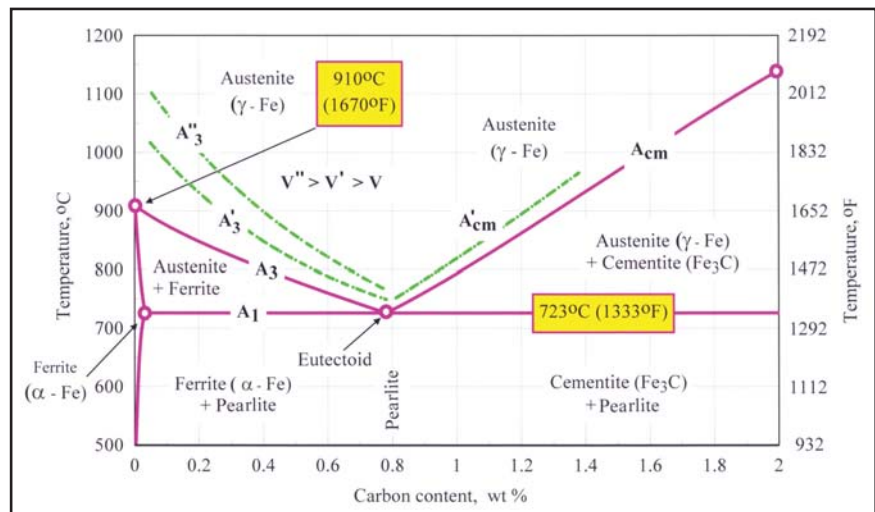


Fig. 1 — The lower left portion of the Fe-Fe<sub>3</sub>C equilibrium phase transformation diagram. Note: A''<sub>3</sub>; A'<sub>3</sub> and A'<sub>cm</sub>; and A<sub>3</sub> and A<sub>cm</sub> at heating rates (°F/s or °C/s) V'', V', and V, respectively (V''>V'>V).

in the majority of induction hardening applications because it is valid *only* for the equilibrium condition of plain carbon steels. Nonequilibrium conditions, appreciable amounts of alloying elements, pressure, and certain prior treatments can noticeably shift the critical temperatures.<sup>2</sup>

One of the major requirements of an equilibrium condition is enough time at temperature. Ideally, in the case of a sufficiently slow heating/cooling, transformation temperatures should be approximately the same for both heating and cooling; in other words, there should be no appreciable difference between  $A_c$  and  $A_r$  critical temperatures.

Any observed difference between  $A_c$  and  $A_r$  represents thermal hysteresis that is a function of several factors including the metal's chemical composition and the heating/cooling rate. The greater the rate of heating/cooling the greater will be the difference between the two critical temperatures. Practically speaking, the equilibrium condition simply does not exist in induction hardening.

## Rapid heating defines induction

Induction hardening is a very fast process. The intensity of heating or heating rate often exceeds 100°C/s (180°F/s), and in some cases reaches 1000°C/s (1800°F/s) and even higher. Therefore, the phase transformation cannot by any means be considered at equilibrium, and the phenomenon of thermal hysteresis will always be pronounced.

Rapid heating drastically affects the kinetics of austenite formation, shifting it toward higher temperatures in order to create conditions conducive to the required diffusion-based processes and resulting in a homogeneous austenitic structure with a uniform distribution of carbon.

The presence of heterogeneous austenite can result in an as-quenched part having an unacceptable microstructure. Upon quenching, decomposition of heterogeneous austenite first begins in regions of lower carbon concentration. This results in a shift of the continuous

cooling transformation (CCT) curve to the "left" and an increase in the  $M_s$  temperature. The CCT curve for regions having excessive amounts of carbon will be shifted in the opposite direction with a corresponding decrease in the  $M_s$  temperature. The degree of heterogeneity in the microstructure of the as-quenched part can be reduced by increasing the hardening temperature.

Observation of "ghost pearlite" or an "excessive amount of free ferrite" during a metallographic evaluation of as-hardened specimens can also indicate the presence of heterogeneous austenite.

Figure 2 shows the effect of heating rate on the  $A_3$  critical temperature of steel.<sup>3,4</sup> The inability of the classical Fe-Fe<sub>3</sub>C diagram to take into account heating intensity limits its use for predicting the temperatures required for induction hardening applications.

**Benchmark study:** Probably the most comprehensive study regarding the correlation of heat intensity with the ability to obtain homogeneous austenite was conducted by J. Orlich, A. Rose, and colleagues at the Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf, Germany.<sup>5,6</sup> They developed atlases that consist of more than 500 pages of nonequilibrium time-temperature-austenitizing diagrams for a variety of steels after they had been induction heated using heat intensities ranging from 0.05 to 2400°C/s (0.09 to 4320°F/s). Those diagrams should be used by induction hardening practitioners instead of the conventional Fe-Fe<sub>3</sub>C diagram in determining the most suitable hardening temperatures of steels.

## Initial structure is important

The microstructure of steel prior to heat treatment (also referred to as the initial structure, structure of the parent material, or structure of the "green" part) also has a pronounced effect on the results of the heat treatment and the required process parameters. These parameters include but are not limited to the austenitizing temperature and the

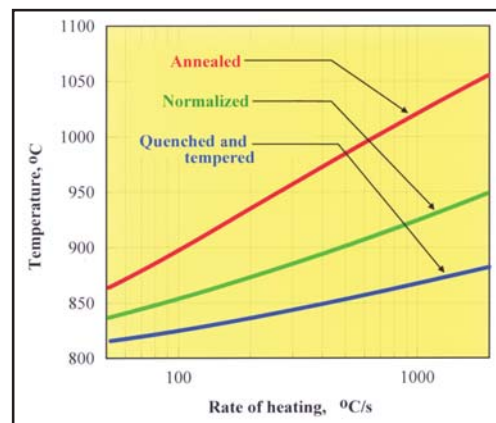


Fig. 2 — Effect of initial microstructure and heating rate on the  $A_3$  critical temperature for AISI 1042 carbon steel. (From Ref. 3 and 4.)

amount of time the part is required to be held at that temperature.

As can be seen in Fig. 2, the required induction hardening temperature range, even for AISI 1042 plain carbon steel, depends on not only the heat intensity but also the material's prior microstructure:

- 1620 to 2000°F (880 to 1095°C), for annealed prior microstructures
- 1550 to 1830°F (840 to 1000°C), for normalized prior microstructures
- 1510 to 1710°F (820 to 930°C), for steels having quenched and tempered prior microstructures

**Q&T structure best:** The effect of prior microstructure can be explained as follows:<sup>1,7</sup>


A quenched and tempered prior structure is the most favorable.<sup>1</sup> It consists of fine pearlite, and ensures rapid transformation, which allows a reduction in the temperature required for austenite formation. This results in a fast, consistent response of the metal to induction hardening with minimum amounts of grain growth, shape/size distortion, and surface oxidation; a minimum required heating energy; and a well-defined — "crisp" — hardness pattern having a narrow transition zone. This type of initial structure can also result in higher hardness and a deeper hardened case depth compared with other prior structures.

**Unfavorable structures:** If the initial microstructure of a steel component has a significant amount of coarse pearlite and, most importantly, coarse

ferrites or clusters or bands of ferrites, then the structure cannot be considered "favorable." Ferrite is practically a pure iron and does not contain the carbon required for martensitic transformation. Pure ferrite consists of less than 0.025% C. Large areas (clusters or bands) of ferrite require a long time for carbon to diffuse into carbon-poor areas. Those ferrite clusters or bands could act as one very large grain of ferrite and will often be retained in the austenite upon rapid heating.<sup>1</sup> After quenching, a complex ferritic-martensitic microstructure can form. Scattered soft and hard spots and poor mechanical properties characterize this structure. Appreciably higher temperatures and longer heating times are required to "austenitize" steels having these structures. It is strongly recommended to avoid segregated and banded initial microstructures in "green" parts.

Steels with large stable carbides (spheroidized microstructures) also

have poor response to induction hardening and also result in the need for prolonged heating and significantly higher temperatures to complete austenitization. Longer heating times lead to grain growth, the formation of coarse martensite, a larger 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.

Therefore, when determining appropriate induction hardening temperatures for a carbon steel component it is imperative to bear in mind the limitations of the equilibrium Fe-Fe<sub>3</sub>C phase transformation diagram, and the need to take into account heating intensity and the microstructure of the "green" part. 

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