

Principles of Induction Hardening and Inspection

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Introduction

Metals can be heated by the process of electromagnetic induction, whereby an alternating magnetic field near the surface of a metallic (or electrically conductive) workpiece induces eddy currents (and thus heating) within the workpiece. The basic components of an induction system are the inductor (coil), which can take different shapes, an alternating-current (ac) power supply, and the workpiece itself. An electrically conductive workpiece (for example, steel) is placed inside an inductor or in its close proximity, the power is turned on, and in a matter of seconds the part begins to glow red and then changes to orange or yellow without having any contact with the inductor. The heating process involves a complex combination of electromagnetic and heat transfer phenomena, as described in more detail in the article “Principles of Induction Heating” in this Volume.

Induction heating is used in a variety of heat treatment processes, such as annealing, normalizing, surface (case) hardening, through hardening, tempering, and stress relieving (Ref 1–10). Various metallic materials, such as steel, cast iron, copper, aluminum, brass, bronze, and so forth, can be heat treated by induction. Induction hardening of steel components is the most common application, and surface (case) hardening is the dominant application of induction heat treatment of steel (see for example Ref 6).

This article discusses the general aspects of induction hardening—including common methods of measuring case depth and hardness, along with some complications and ambiguities associated with these measurements. As expected, the subject of induction hardening is quite complex, comprising electrothermal phenomena, physical effects, technological subtleties, and knowhow. Due to space limitation, coverage is necessarily limited in this article. However, several other articles in this Volume cover more material related to certain aspects of induction hardening, including:

- Metallurgy of induction hardening
- Induction hardening of axle shafts

- Induction hardening of crankshafts and camshafts
- Induction hardening of gears and gearlike components
- Induction hardening of off-road machinery
- Coil design, systematic analysis of induction coil failures, and failure prevention
- Quenchants and quenching devices
- Formation of residual and transitional stresses
- Computer modeling
- Power supplies for induction heat treating
- Process control and monitoring
- Maintenance of heat treating equipment
- Defects and abnormal characteristics of induction-hardened components
- Tempering of induction-hardened components

With the expanded coverage from other articles in this Volume, an interested reader can obtain a more detailed understanding of induction hardening.

Metallurgical Overview

The general aspects of metallurgy of induction hardening of steels are discussed in several publications (Ref 1–11). The typical induction-hardening procedure involves heating the component, or its required area, up to the austenitizing temperature, holding it at a temperature (if required) for a sufficient period for completion of austenite formation, then rapidly cooling it below the martensite start (M_s) temperature (see the subsequent article “Quenching in Induction Hardening” in this Volume). Rapid cooling or quenching allows replacement of the diffusion-dependent transformation process by a shear-type transformation, creating a much harder constituent called martensite. Martensite can be formed and hardening may be done either on the surface of the workpiece or throughout the entire cross section.

The main factors that affect the hardness and case depth are the temperature distribution, the starting microstructure of the material, the

chemical composition, the quenching conditions, and the hardenability of the steel. Temperature distribution in induction surface hardening is controlled by selection of frequency, power density, time of heating, and coil geometry. Typical induction surface-hardening temperatures range from approximately 880 to 1050 °C (1620 to 1920 °F). The color associated with this range is orange to yellow.

The surface hardness, case depth, and core requirements will typically determine the grade of steel to be used. The attainable hardness increases along with the carbon content of the steel. This holds true up to approximately 0.65 to 0.7% C and then there is little or no further increase in hardness with increasing carbon content. For any given carbon level, induction surface hardening provides a slightly higher hardness than would be expected with traditional furnace hardening. This phenomenon is sometimes referred to as superhardening (Ref 12).

The microstructure present in a part prior to induction hardening can have a significant influence on how well a part hardens (Fig. 1). The most common prior microstructure is a mixture of pearlite and ferrite. The reason for this is not the ease of induction hardening but rather economics. A pearlitic-ferritic microstructure generally requires no additional heat treatment after the part is forged. In components manufactured directly from bar stock the microstructure is usually already a mixture of pearlite and ferrite. While a pearlitic-ferritic structure is not the best for ease of induction hardening it is certainly adequate for many applications. The prior structure that provides the best response for induction hardening is a quenched and tempered (QT) microstructure consisting of tempered martensite or possibly an austempered microstructure consisting of bainite. These microstructures are very easy to austenitize in the short heating time associated with induction hardening, and as a result they can be readily converted to martensite upon quenching. In most cases the quenchants used are water-based polymers, so there is typically no fire hazard or environmental concern.

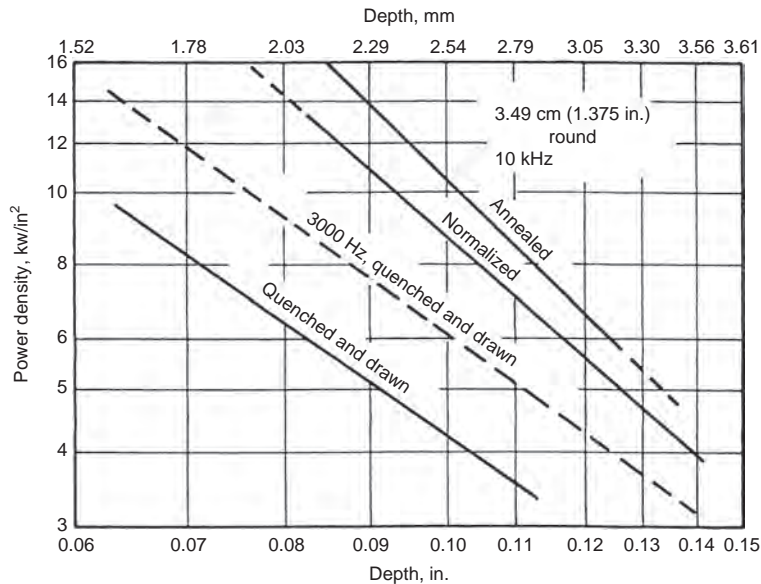


Fig. 1 Influence of prior structure (fineness of microstructure constituents) on power requirements for surface hardening. Source: Ref 13

An annealed prior microstructure consisting of ferrite and spheroidal carbides has the poorest response to induction hardening. This type of microstructure can be formed by subcritical annealing. Spheroidized annealing is typically used to aid in cold formability. It is not uncommon for this type of microstructure to be only partially martensitic after induction hardening. Substantially longer times and higher temperatures are required for a sufficient austenitization of these microstructures, noticeably dropping some of the main advantages of induction hardening. The poor induction-hardening response can be alleviated by normalizing the part after forming.

The full anneal method produces a microstructure consisting of ferrite and pearlite. The carbon content determines the amount of pearlite. This type of microstructure induction hardens easier than the spheroidal microstructure, but not as well as the normalized microstructure.

Steel selection depends on specifics of the working conditions of the component, required hardness, and cost (Ref 1–11, 14, 15). Most induction surface hardening is done with steels containing 0.35 to 0.60% C. The corresponding minimum hardness, after tempering at 180 °C (360 °F), would be a Rockwell C hardness (HRC) of approximately 48 to 60. Plain carbon steels are the least expensive steels used successfully for a variety of hardening applications. It is important to remember that the carbon content of steel plays a critical role in the maximum achievable hardness and it also affects the amount of retained austenite and the depth of hardening.

Medium-carbon steels (i.e., SAE 1035 to 1060) are the most common steels used in industry. Low-carbon steels are used where toughness rather than high hardness is required, such as in clutch plates or pins for farm equipment. High-carbon steels are somewhat limited by their low ductility and toughness, poor machinability,

and poor formability. Even so, there are a variety of applications including valve-spring wire, drill bits, grinding balls, cutting tools, and others, for which high-carbon steels (such as SAE 1060 to 1095) are specified.

Although plain carbon steels are the least expensive steels, there may be engineering applications where they may not be suitable. Applications which require more hardenability for increased case depths, or greater impact resistance, or higher fatigue life, may require the use of alloy steels. Examples of alloy steels used in induction hardening are SAE 4140, 4150, 4340, 5150, 5140, and 52100.

Typical Applications. Induction hardening can be used for a wide range of parts, and prominent examples are discussed in separate articles in this Volume. Examples include machine tools, hand tools, crankshafts, camshafts, axle shafts, transmission shafts, universal joints, gears, sprockets, pins, valve seats, steering knuckles, spindles, bearings, track links, connecting rods, fasteners, and many others. In some cases, it is desirable to harden an entire cross section of a component; however, other applications require only selected areas (e.g., the surface) to be hardened. For example, with a part such as an axle shaft, typically the entire length is surface or case hardened. On a component such as a crankshaft, the bearing journals are selectively hardened. Figure 2 illustrates some examples of the many types of ferrous components that can be induction hardened. Components are induction hardened for different reasons. Induction surface hardening, also sometimes called induction case hardening, increases the hardness and strength at the surface. Surface hardening is an important method of improving torsional strength and/or torsional fatigue life, as well as bending strength and/or bending fatigue life. In torsion and in bending, the stress is greatest at the surface and is zero at

the center. For this reason surface hardening can improve part performance with these two load cases, because it increases the strength at the surface where it is needed the most.

In addition, surface hardening normally leaves the surface of the part with a residual compressive stress, which acts as a crack arrester and increases torsional and bending fatigue life. The residual compressive stress is a result of the expansion that takes place during the transformation of the microstructure to martensite during hardening. Another reason for induction surface hardening is to improve wear resistance or contact strength and/or contact fatigue life.

Induction through hardening also may be used for some parts such as snowplow blades, springs, chain links, truck bed frames, certain fasteners (including nails and screws), and so forth. In these cases, the temperature of the entire cross section is raised above the temperature at which transformation to austenite is completed (A_{c3} critical temperature) and then quenched. Through-hardening applications require uniform heating through the entire cross section. Selection of the appropriate frequency and time is very important for achieving the proper surface-to-core temperature uniformity.

Electromagnetic and Thermal Aspects

As detailed in the article “Principles of Induction Heating” in this Volume, the primary mechanism of the heat generation is Joule heating ($I^2 R$) by the induced eddy current, where R is electrical resistance of the workpiece and I is the induced current. An alternating current (ac) in the induction coil produces an alternating magnetic field (with the same frequency as the coil current), which induces eddy currents in the workpiece in or near the coil. The induced currents have the same frequency as the coil current; however, their direction is opposite to the coil current (according to Faraday’s law of electromagnetic induction). In fact, the coil acts in much the same manner as a primary winding of a transformer, with the electrically conductive workpiece acting as a single-turn (or short-circuited) secondary winding. An important factor associated with the heat pattern control is the degree of coil-to-workpiece electromagnetic coupling and heat time. Coupling is determined by the number of imaginary magnetic flux lines that enter the workpiece or its portion.

Joule heating from the induced eddy currents occurs for any electrically conductive material and is not limited to only magnetic material. Heating intensity is typically controlled by the coil voltage/current and applied frequency. The induced eddy currents generate heat not only at the surface but also in the subsurface regions. In addition, a second mechanism of heat generation occurs in ferromagnetic materials (e.g., carbon steels) when energy is dissipated during the reversal of magnetic domains and is called magnetic

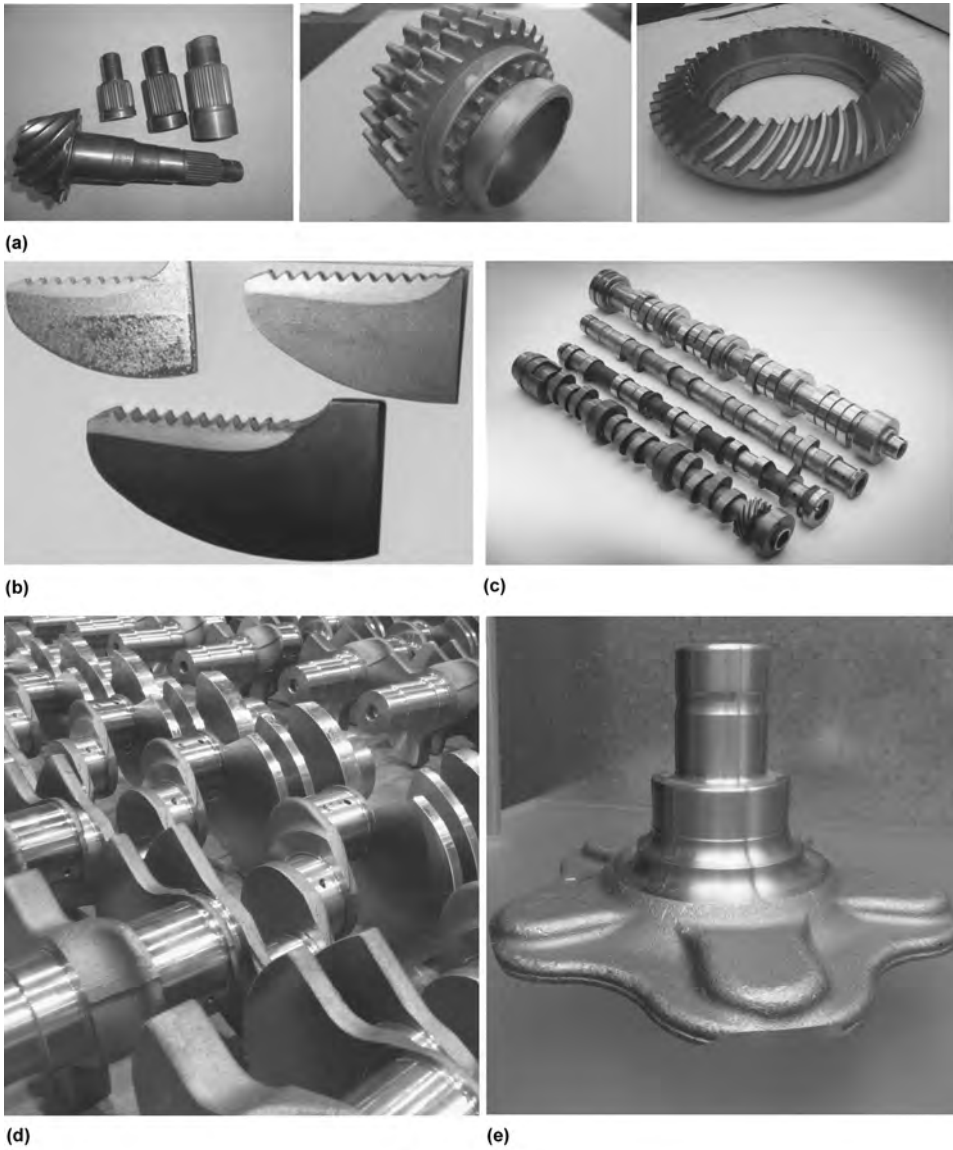


Fig. 2 Examples of induction-hardened components. (a) Gear and gearlike components. (b) Wrench jaws. (c) Camshafts. (d) Crankshaft. (e) Machine component. Courtesy of Inductoheat, Inc.

hysteresis energy losses. An old-fashioned, but still useful, explanation of the hysteresis loss states that it is caused by friction between molecules when the material is magnetized first in one direction and then in the other (Ref 4). The molecules may be regarded as small magnets that turn around with each reversal of direction of the alternating magnetic field. The energy required to turn them around is converted into heat.

The first mechanism of the heat generation, eddy current losses (I^2R), has a much greater impact on overall heat generation during induction hardening compared to hysteresis losses, in particular when approaching or exceeding the Curie temperature (A_c2 critical temperature).

The induction heating intensity and temperature distribution (heat pattern) depend on several factors, including, but not limited to:

- The electrical and magnetic properties of the heated material, such as electrical resistivity (ρ) and relative magnetic permeability (μ_r)
- The thermal properties (including thermal conductivity and specific heat)
- Proximity of the workpiece to the induction coil, their geometries, and design specifics
- Power density
- Frequency of electromagnetic field (EMF). Lower frequencies tend to heat deeper, while higher frequencies favor shallow case depths according to an electromagnetic skin effect.

Common Definition of the Skin Effect.

From the basics of electricity, when a direct current (dc) flows through a solid conductor that stands alone (bus bar or solid cable), the current distribution within the cross section of the

conductor is uniform. However, when an ac flows through the same conductor, the current distribution is not uniform. The maximum value of the current density is located on the surface of the conductor, and current density decreases from the surface toward the center. This phenomenon of nonuniform current distribution within the conductor cross section is called the skin effect. The skin effect must be clearly understood because it affects all of the most critical characteristics of an induction system.

According to a commonly accepted definition of the skin effect, approximately 86% of all power induced by an induction coil will be concentrated in the surface layer (the “skin”). This layer is called the reference depth or current penetration depth and is typically designated by the symbol δ . The skin effect is considered as a fundamental property of any process that relies on heating by electromagnetic induction. This effect is also observed in any electrically conductive body (workpiece) located inside or in close proximity to an induction coil. The value of δ varies with the square root of electrical resistivity (ρ) and inversely with the square root of frequency (F) and the relative magnetic permeability (μ_r), according to:

$$\delta = 503 \sqrt{\frac{\rho}{\mu_r F}} \quad (\text{Eq 1})$$

where ρ measures in $\Omega \cdot \text{m}$, μ_r is unitless, F measures in Hz, and δ measures in meters.

Frequency and temperature have a dominant effect on a magnitude of δ in steels and cast irons. By controlling the depth of current penetration it is possible to austenitize selective areas of the component that require being hardened without affecting the rest of the component. Depending on a required hardness depth, the frequency selection for surface-hardening applications ranges from 60 Hz (hardening of large mill rolls) to greater than 600 kHz (hardening small pins and wires).

Figure 3 illustrates a classical definition of the skin effect appearance by showing distribution of current density toward the surface of the cylinder workpiece toward the core (Ref 1, 16). At a distance equal to one penetration depth below the surface ($y = \delta$), the current will equal 37% of its surface value. However, the power density equals only 14% of its surface value. From this it can be concluded that approximately 63% of the current and 86% of the power in the workpiece will be concentrated within a surface layer of thickness δ .

Because electrical resistivity (ρ) is a function of temperature and relative magnetic permeability (μ_r) is a function of temperature and magnetic field intensity (Ref 1), the penetration depth is not a constant but rather a nonlinear function of temperature and magnetic field intensity. During the hardening cycle a workpiece or its portion is heated from ambient temperature to temperatures appropriate for austenitization. Variations of ρ and μ_r with temperature (Ref 17) cause a dramatic increase of the δ compared to

its initial value. In hardening applications, this increase often exceeds five times. Table 1 shows typical values of current penetration depths for plain medium-carbon steel at different stages of heating versus frequency.

At temperatures below the Curie point, an increase in carbon content of the plain carbon steels typically leads to a greater δ caused by a corresponding increase of ρ and a reduction of μ_r . Carbon content reduction results in an opposite effect. Variations of carbon content in plain carbon steels usually produce approximately 12 to 16% variation of δ . For alloy steels those differences may be greater.

Surface Hardening and Magnetic-Wave Phenomenon. It is important to note that commonly accepted assumptions regarding current and power distribution due to a skin effect are not valid for the great majority of induction surface-hardening applications (Ref 15, 16). For example, an exponential distribution of eddy current and induced power is only appropriate for a solid body (workpiece) having constant values of both electrical resistivity and magnetic permeability. Therefore, realistically speaking, this assumption can be made for only some unique cases of induction heating of nonmagnetic materials. Therefore, a classical definition of δ can only be used for rough estimates in appropriate cases.

For the great majority of induction surface-hardening applications, the power density distribution is not uniform and substantial thermal gradients are present within the heated workpiece.

These thermal gradients result in nonuniform distributions of electrical resistivity and, in particular, magnetic permeability, leading to the fact that the common definition of δ being an exponential curve does not "fit" its principle assumption.

In applications such as surface hardening and heating carbon steels to working temperatures just above the Curie point, the power density distribution along the radius/thickness has a unique wave shape, which is appreciably different compared to the commonly assumed exponential distribution (Ref 1, 15, 16). The maximum power density is located at the surface and decreases toward the core. However, at a certain distance from the surface, the power density increases, reaching a maximum value before again decreasing. This magnetic-wave phenomenon was introduced by Simpson (Ref 18), and Losinskii (Ref 19). Both scientists intuitively felt that there should be conditions where the power density (heat source) distribution would differ from that of the commonly accepted. They provided a qualitative description of a magnetic-wave phenomenon based on intuition. At that time, it was difficult to obtain a quantitative estimation of this phenomenon due to limited computer modeling capabilities. Also, it was not possible to measure the power/current density distribution inside the solid body during the heating cycle. The first publication that provides the results of the research studies with a quantitative estimation of this magnetic-wave phenomenon was published in the mid-1990s (Ref 20).

The existence of the magnetic-wave phenomenon is associated with the presence of magnetic properties in subsurface regions of a workpiece, while the surface reaches austenitizing temperatures thus being nonmagnetic. Reference 16 provides a case study of heating a 36 mm (1.4 in.) diameter medium-carbon steel shaft using a frequency of 10 kHz. Temperature and the power density (heat source) distribution along the radius are plotted in Fig. 4 at the final stage to produce a required case depth of 2 mm (0.08 in.). Temperature profile (Fig. 4a) indicates the temperature region of magnetic-to-nonmagnetic transition. In Fig. 3(b), there is the second maximum of power density located at a distance of approximately 3 mm (0.12 in.) below the surface. This location coincides with the subsurface temperature of the magnetic core region with the austenitic (nonmagnetic) surface region. The resulting power density distribution (Fig. 4b, solid curve) is dramatically different compared to commonly assumed distribution (dotted curve).

In applications such as through hardening or steel normalizing, the impact of the magnetic-wave phenomenon on the final temperature distribution and overall process parameters is much less pronounced, because when steel is heated above the Curie point the nonmagnetic stage is substantially longer compared to a magnetic stage.

In surface hardening, the magnetic-wave phenomenon exists during the majority of the heat cycle and plays a very important role in the selection of the optimal frequency and prediction of final temperature distribution and hardened case depth.

As an example, Fig. 5 shows the dynamics of the radial temperature distribution during single-shot hardening of a medium-carbon steel shaft using a frequency of 125 kHz. The required case depth is 1.2 mm (0.05 in.), the material is SAE 4340, the heating time is 2 s, the quench time is 6 s, and the shaft diameter is 16 mm (0.63 in.).

Table 1 Typical values of current penetration depths for plain medium-carbon steels during initial and final heat stages for induction hardening

| Stage of heating | Heat intensity | Current penetration depths at various frequencies | | | | | | | | | |
|------------------|----------------|---|------|-------|------|--------|------|--------|------|---------|------|
| | | 0.5 kHz | | 3 kHz | | 10 kHz | | 30 kHz | | 200 kHz | |
| | | mm | in. | mm | in. | mm | in. | mm | in. | mm | in. |
| Initial | Moderate | 3.3 | 0.13 | 1.3 | 0.05 | 0.7 | 0.03 | 0.4 | 0.02 | 0.17 | 0.01 |
| | High | 3.9 | 0.15 | 1.6 | 0.06 | 0.9 | 0.04 | 0.5 | 0.02 | 0.2 | 0.01 |
| Final | ... | 24 | 0.94 | 9.9 | 0.39 | 5.4 | 0.21 | 3.1 | 0.12 | 1.2 | 0.05 |

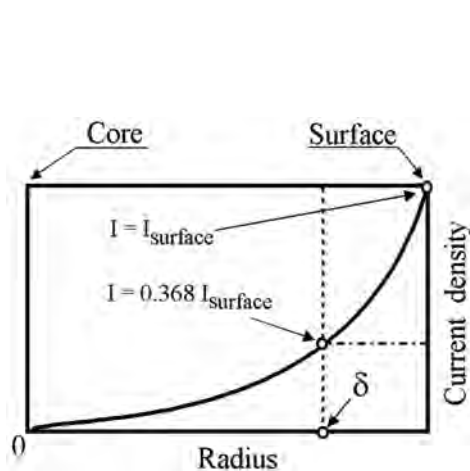


Fig. 3 A classical definition of the skin effect appearance showing distribution of current density from the surface of the cylinder workpiece toward the core. Source: Ref 1

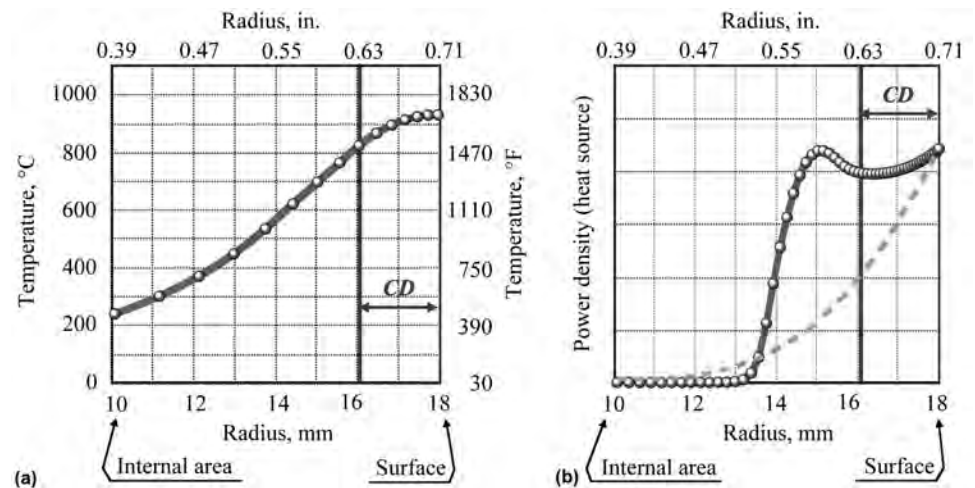


Fig. 4 Radial temperature distribution (a) and power density profile (b) for induction surface hardening of carbon steel shafts using 10 kHz frequency. Case depth (CD) is 2 mm (0.08 in.). The dashed line in the graph is the commonly assumed power density distribution. Source: Ref 1, 17

After 2 s of heating, the surface layer of the shaft reaches the required thermal condition for austenitizing. Due to the skin effect, intense heating, and short time, the core temperature does not exceed approximately 525 °C (980 °F) at the end of heating. The core and near-core regions were heated due to thermal conductivity from the high-temperature surface layer.

As can be seen from Fig. 5, on approaching the Curie temperature, the intensity of heating (heat rates) of the surface and near-surface regions decreases greatly. There are four factors responsible for this behavior:

- The first factor is associated with the loss of magnetic properties of steel and subsequent dramatic reduction of the electrical resistance to eddy current flow. When steel loses magnetic properties, current penetration depth dramatically increases (see Table 1). Therefore, induced eddy currents start flowing within a much larger area (cross section), which is inevitably associated with a reduction of electrical resistance leading to lower heating intensity, regardless of the continual increase of the electrical resistivity (ρ) of steel with temperature. Reduction of the electrical resistance due to an increased area of current flow overpowers the increase in ρ . This is one of the main causes of the reduction of the heat intensity around a Curie point.
- The second factor is related to a localized spike of the specific heat of steel. As an example, Table 2 shows a variation of the specific heat for several induction-hardenable steels (Ref 17, 21). Specific heat directly affects the kilowatts required to raise the temperature and the intensity of heating always decreases within approximately ± 40 to ± 60 °C (± 70 to ± 110 °F) of the temperature of the maximum of the specific heat (depending on the steel grade). It is not unusual that the maximum value of the specific heat is 200% greater than its values outside of that region.
- Surface heat losses (due to thermal radiation and convection) are continually increasing with temperature, requiring a greater amount of induced power to compensate.
- There are two mechanisms of heat generation below the Curie temperature: eddy current heat generation (Joule effect) and hysteresis heat. On approaching the Curie point, the impact of heat generation due to magnetic hysteresis starts to be less significant and finally disappears after the temperature exceeds the Curie point.

In some low power density applications, a plateau on the time-temperature diagram may occur after the surface temperature reaches the Curie temperature and usually lasts until the surface temperature exceeds approximately 780 to 820 °C (1440 to 1510 °F). However, in the great majority of induction surface-hardening applications, the magnitudes of the applied power densities are sufficiently high to dramatically suppress or eliminate an occurrence of the

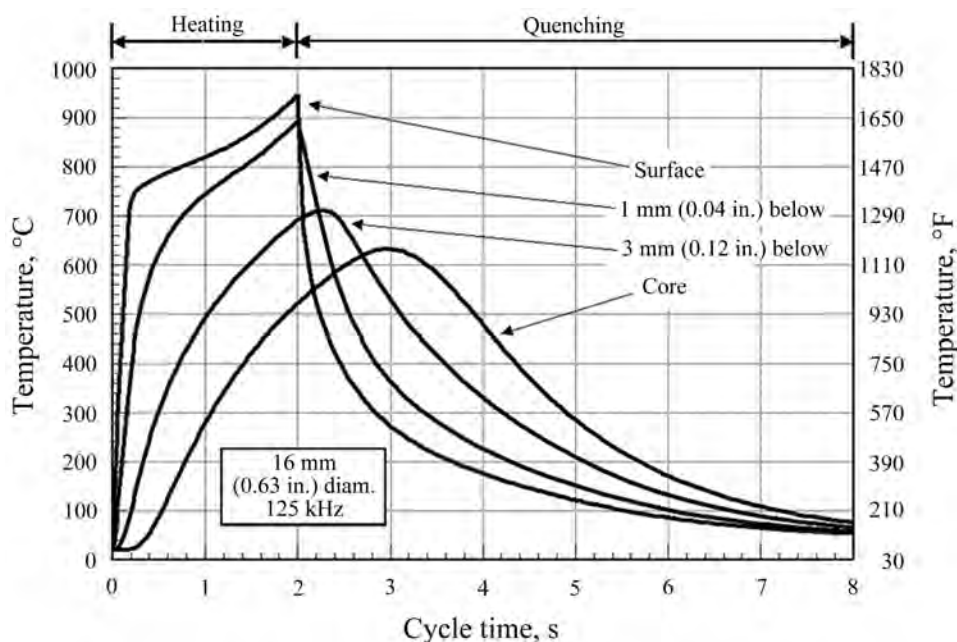


Fig. 5 Dynamics of the radial temperature distribution during single-shot hardening of a medium-carbon steel shaft using a frequency of 125 kHz assuming constant coil current. Required case depth: 1.2 mm (0.05 in.); material: SAE 4340; heating time: 2 s; quench time: 6 s; shaft diameter: 16 mm (0.63 in.)

Table 2 Changes in specific heat of steels with temperature

| Temperature | | Specific heat (J/kg °C) for AISI-SAE steels | | | | |
|-------------|-----------|---|-------------|-------------|-------------|-------------|
| °C | °F | 1026 | 1040 | 1078 | 1524 | 5132 |
| 50–100 | 120–212 | 486 | 486 | 490 | 477 | 494 |
| 200–250 | 390–480 | 532 | 528 | 548 | 528 | 536 |
| 300–350 | 570–660 | 574 | 569 | 586 | 565 | 574 |
| 450–500 | 840–930 | 662 | 649 | 670 | 649 | 657 |
| 550–600 | 1020–1110 | 749 | 708 | 712 | 741 | 741 |
| 650–700 | 1200–1290 | 846 | 770 | 770 | 837 | 837 |
| 700–750 | 1290–1380 | 1432 | 1583 | 2081 | 1449 | 1499 |
| 750–800 | 1380–1470 | 950 | 624 | 615 | 821 | 934 |
| 850–900 | 1560–1650 | ... | 548 | ... | 536 | 574 |

Source: Ref 17, 21

temperature plateau. Instead of the temperature plateau, there is only a variation in the slope of the time-temperature curve.

In the case under consideration (Fig. 5), the quenching begins immediately after a completion of the heating cycle, manifesting itself in a dramatic reduction of the surface and near-surface temperatures. Simultaneously, there is an appreciable time delay in cooling of internal regions. This delay is greater and the cooling severity is increasingly reduced for regions positioned closer to the core of the shaft. For example, the core temperature is still continually rising during the first second of quenching. The radial temperature distribution at this point resembles a wave with the maximum temperature being positioned inside of the shaft. This wavelike distribution of temperature has nothing to do with the magnetic-wave previously discussed, because its presence is associated with the heat transfer due to thermal conduction during surface quenching and accumulated

residual heat. Two heat transfer phenomena are occurring simultaneously at this point: an intense cooling of the surface and subsurface regions (e.g., 1 mm, or 0.04 in., below the surface) and the continued heating of the core. After 3 s of quenching (cycle time = 5 s) the surface temperature is reduced to approximately 120 °C (250 °F), while the core is still at approximately 300 °C (570 °F). If quenching is stopped at this point, then the residual heat can result in tempering back of the martensite at the surface. This phenomenon emphasizes the importance of having a sufficient quenchout time.

It is important to note that in some applications, an accumulated residual heat can be advantageous for providing a desirable self-tempering or autotempering. Reference 1 provides detailed discussion regarding this phenomenon. The dynamics of martensite formation in a majority of induction surface-hardening applications results in the formation of a substantial surface compressive residual stress. This can be

very beneficial for parts that are subjected to cyclic loading. Coil current was intentionally kept constant in this study. Dynamics of heating and time-temperature curves will be different to some degree if voltage or power at the coil terminals is kept constant, though physics of the process will remain the same.

Through Hardening. The skin effect can play an important role in through-hardening applications as well. Figure 6 shows the results of computer modeling of an induction through-hardening treatment on the same shaft as the example shown in Fig. 5. Regardless of the applied frequency there will be no eddy current flow and heat generation in the core. The core of the solid shaft is only heated by thermal conduction from the higher temperature regions.

To provide sufficient radial heat flow during through hardening, longer heat times and lower frequencies than surface hardening are typically required. Therefore, one of the most important requirements of through hardening is sufficient austenitization of the core without excessively high temperatures at the part surface. Another distinguishing feature is associated with using polymer quenchants having lower temperature and lower concentration to ensure a sufficient cooling intensity of the through heated part. In addition to the necessity for proper austenitization and sufficient quench intensity, the ability of the part to be through hardened also depends on the hardenability of the steel.

In contrast to the case study of surface hardening (Fig. 5), the frequency for through hardening has been reduced from 125 to 10 kHz. This provides a substantially more in-depth heating effect by increasing δ above the Curie point from approximately 1.7 to 5.4 mm (0.07 to 0.21 in.), which, in turn, increases the ratio R/δ from 4.7 to 1.48. Increased δ helps to dramatically improve surface-to-core temperature uniformity, particularly upon reaching temperatures in the austenitizing range. Heat time has also been increased from 2 to 8 s, helping thermal conductivity by providing sufficient heat flow toward the core.

In-depth heating and uniform temperature distribution are achieved by using lower frequencies. The application of lower frequencies also allows the heating time to be reduced, which decreases excess heat at the workpiece surface.

However, if the frequency is too low an eddy current cancellation may occur. This is an undesirable phenomenon that can dramatically reduce heating efficiency. Figure 7 shows the relative radial power density (heat source) distribution within the shaft at austenitizing temperature using different frequencies: 125, 30, 10, and 1 kHz. In some extreme cases, after achieving a certain level, no additional temperature increase can be recorded because the heated workpiece acts as a transparent or semitransparent body to the EMF of the induction coil.

Eddy current cancellation can be avoided by selecting a frequency for through hardening a solid cylinder of radius (R) such that the radius/skin depth ratio is greater than 2 ($R/\delta > 2$).

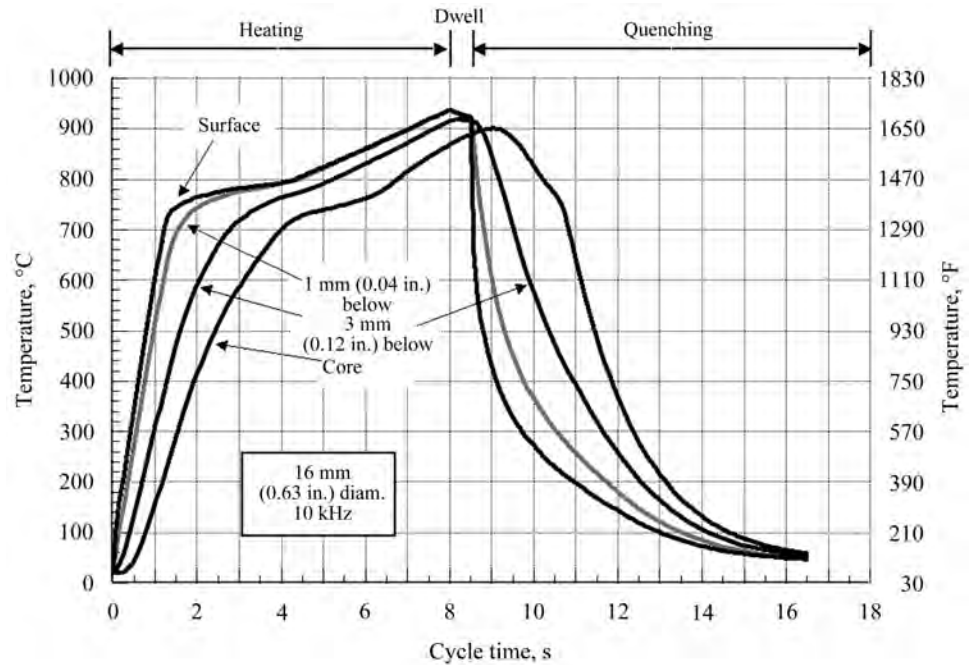


Fig. 6 Results of computer modeling of induction through hardening on the same shaft as the example shown in Fig. 5

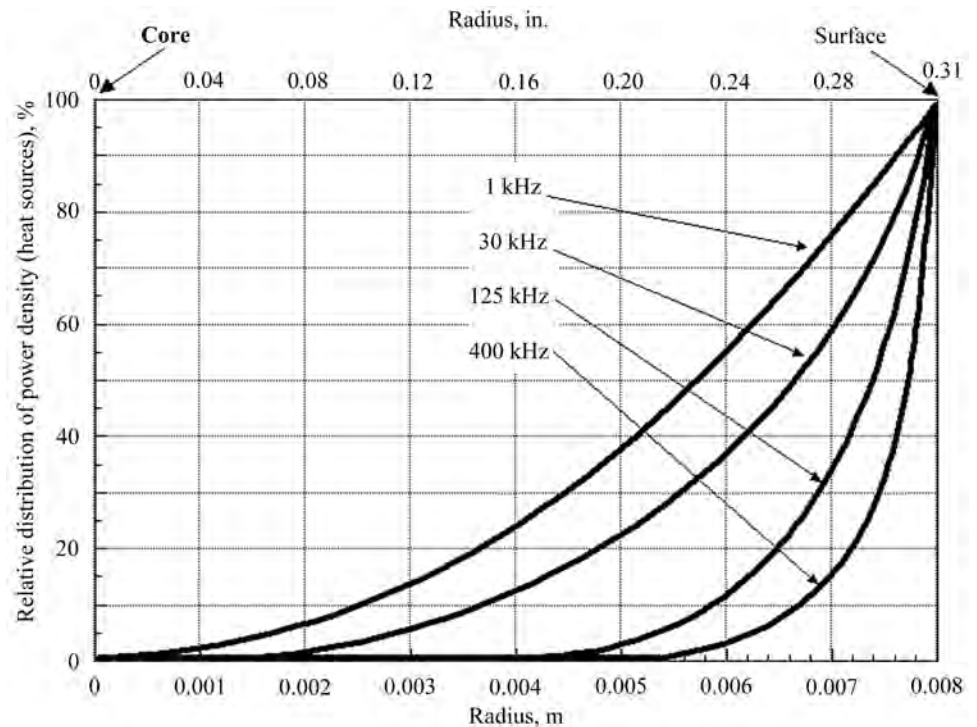


Fig. 7 Radial power density (heat source) distribution within the shaft at austenitizing temperature using different frequencies: 125, 30, 10, and 1 kHz

Insignificant current cancellation occurs if $2 > R/\delta > 1.5$. In the case study shown in Fig. 6, the ratio is $R/\delta = 1.48$, which is slightly lower than the recommended range. Therefore, some eddy current cancellation occurs in this case.

The current cancellation phenomenon is more complex when through hardening hollow cylinders. Its occurrence is a nonlinear function of the ratios of outside diameter to δ and wall thickness to δ , and the specifics of the inductor design.

In some cases, a short time delay (also called a dwell or soak) is used in through-hardening applications, which helps to further improve the radial temperature uniformity and reduce the thermal shock during the initial stage of quenching. As seen in Fig. 6, there is a short 0.5 s dwell (soak) on completion of the heat cycle, which further helps to improve radial heat uniformity prior to quenching. The nonlinear disturbance in the time-temperature cooling curves (in particular the core cooling curve) is primarily associated with the previously discussed nonlinearity of the specific heat. Figure 6 also reveals that in through-hardening applications, the martensite forms first in the surface where quench severity is always greater compared to the core. The core and near-core areas are the last regions where martensitic transformation occurs. Therefore, the surface has a tendency to have a slightly higher hardness than the core. The dynamics of martensite formation in through-hardening applications also affect the distribution of residual stresses and, depending on quench severity, can put the surface into tension and the core into compression.

Electromagnetic Proximity Effect. In the discussion related to the skin effect, it was assumed that an electrical conductor stands alone and there are no other current-carrying conductors in the surrounding area (Fig. 8a). In most practical applications this is not the case. Most often there are other current-carrying conductors located in close proximity. These conductors have their own magnetic fields that interact with nearby fields, distorting the current and power density distributions. Figure 8(b and c) shows the effect on current density distribution in a conductor when another conductor is placed nearby. When a second current-carrying conductor is placed near the first one, the currents in both conductors will redistribute.

If the currents flowing in the conductors have the same direction (Fig. 8b), the currents will be concentrated on opposite sides (Ref 1). However, if the currents have opposite directions (Fig. 8c), then both currents will be shifted toward the areas facing each other, producing a localized maximum of the power density there.

The phenomenon of the proximity effect is directly applied in induction hardening. It is one of the most powerful physical mechanisms for controlling hardness patterns and is widely used in profiling hardening inductors. The proximity effect is also often responsible for the appearance of hot and cold spots.

Due to Faraday's law of electromagnetics, eddy currents induced within the workpiece are in the opposite direction to that of the induction coil current. Therefore, due to the proximity effect, the coil current and eddy currents induced in the workpiece will concentrate in the areas facing each other.

Higher frequencies and closer distances between current-carrying conductors (e.g., portions of the inductor and the workpiece) intensify the appearance of the proximity effect. Figure 9 presents the results of computer

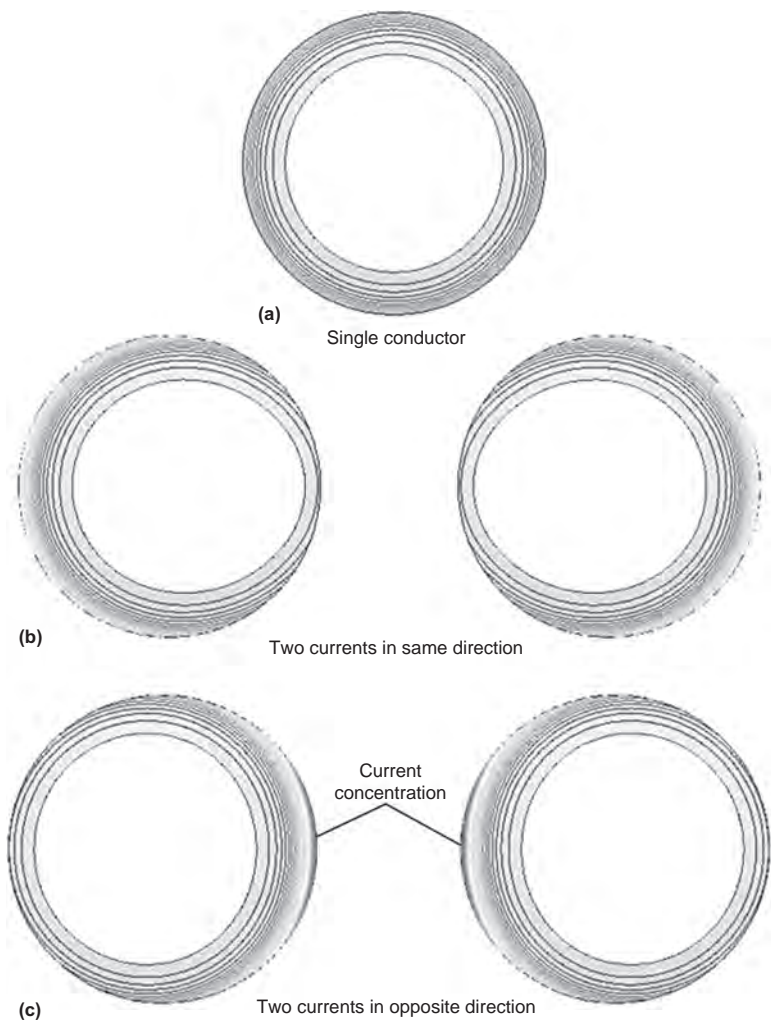


Fig. 8 Computer simulation of the electromagnetic proximity effect. (a) Power density distribution (skin effect) in a stand-alone solid conductor carrying an alternating current. (b) Two conductors with current flowing in the same direction. (c) Two conductors with current in the opposite direction

modeling showing current density distribution and the proximity effect when two bus bars have currents flowing in opposite directions. The left bus was tilted with respect to the right one, resulting in a nonconstant gap (proximity) between both bars. Significant redistribution of the current density to the region with the smallest gap can be observed.

Generally, an induction-hardening system can be considered as consisting of two current-carrying conductors. One of these conductors is the heating inductor (single-turn or multiturn) that carries the source current, and the other is the heated workpiece that is located inside (e.g., a solenoid coil), or in proximity to (e.g., a pancake coil), the inductor. As stated previously, induced eddy currents have an orientation opposite to the coil current. Therefore, due to the proximity effect more intense heating will occur in the area that has better inductor-to-workpiece electromagnetic coupling (smaller gap).

Due to the proximity effect, certain design features make some regions of the part more prone to overheating. Typical examples are parts

containing keyways, grooves, shoulders, flanges, diameter changes, and undercuts. The presence of these features distorts the magnetic field generated by an inductor, appreciably affecting the proximity effect. The proximity effect can manifest itself not only as a heat surplus but also as a heat deficit that can occur in the undercut region of the shaft and transition area near the smaller diameter of the shaft, potentially resulting in mixed, partially transformed structures upon quenching (Ref 23).

The complexity of the EMF distribution in the areas where geometrical irregularities are present requires a specific coil design and appropriate process recipe addressing the possibility of having the surplus of induced power in the better coupled regions (e.g., the shoulder of the larger diameter) and a power deficit in the fillet or undercut of the neighboring smaller-diameter area.

Figure 10 shows another example of using a multiturn coil profile to control the heat pattern using the electromagnetic proximity effect (Ref 24). An uneven heating pattern (a

thumbnail pattern) in a round bar is obtained by using a conventional coil winding (Fig. 10a). This problem can be corrected by varying a coupling of coil turns (Fig. 10b). Figure 11 shows an example of two inductor designs that rely primarily on the proximity effect for obtaining required hardness patterns. Figure 11(a) is used for hardening constant velocity joint races while Fig. 11(b) is used for hardening gear teeth.

Electromagnetic End Effect. Aside from the factors discussed previously, temperature distribution within the workpiece can also be affected by the electromagnetic end effect (Ref 1). End effect represents a distortion of the electromagnetic field at the end regions of the inductor and/or the heated component. Figure 12(a) shows a sketch of the induction system for heat treating the end of a pipe. A complexity of the magnetic field distribution when steel is below the Curie temperature is shown in Fig. 12(b).

Electromagnetic end effect can manifest itself as underheating or overheating of the workpiece end area. Figure 13 illustrates the relative surface power density distribution along the heated length of the pipe (Ref 16). The electromagnetic end effect at the extreme end ("hot" end) of the pipe (Fig. 13, region A-B) is defined primarily by the following

variables, where R is the radius of the heated pipe and R_i is the inside coil radius:

- Skin effect (R/δ)
- Coil overhang (σ)
- Ratios R_i/R and wall thickness to δ
- Power density
- Presence of a flux concentrator
- Space factor of coil turns (K_{space})—density of windings of coil turns—and their coupling

The effects of frequency (F) and the electromagnetic physical properties of the steel (ρ and μ_r) are included in the skin effect ratio (R/δ).

Rule of thumb: With a conventional multiturn solenoid coil, a measurable power deficit at the extreme (hot) end of the heated workpiece, which will therefore be noticeably underheated, may be caused by one of following factors or their combination:

- Low frequency
- Modest power densities
- Large coil-to-workpiece radial gaps
- Insufficient (small) coil overhangs (σ)

In contrast, the use of too high of a frequency and power density, as well as a large coil overhang, can usually lead to a power surplus in the end area. As a result, noticeable overheating may take place.

It is important to understand that a uniform power density (heat source) distribution along the hot end of the workpiece will not correspond to the uniform temperature distribution because of the additional heat losses (due to thermal radiation and heat convection) at the hot end compared to its central region. Proper

selection of coil design and process parameters can help to compensate for the additional surface heat losses at the end by generating an appropriate power surplus due to the electromagnetic end effect. This allows for obtaining a reasonably uniform temperature distribution within the required heated length (RHL) of the workpiece.

Another important feature of the end-hardening effect is the heat distribution under the opposite end of an induction coil that is in the C-D-E zone (Fig. 13). This is sometimes defined as the heat-affected zone (HAZ) or axial transition zone. There is a considerable longitudinal temperature gradient that results in longitudinal heat flow due to thermal conduction from the high-temperature region of the workpiece toward its colder area, manifesting itself as the heat sink phenomenon.

Figure 14 shows the results of finite-element analysis (FEA) simulation of surface hardening the ends of a carbon steel shaft and longitudinal temperature distribution at different stages of heating (1, 4, and 9.3 s) along the surface, 3 mm (0.12 in.) below the surface, and 5 mm (0.20 in.) below the surface. The outside diameter of the shaft is 75 mm (2.95 in.);

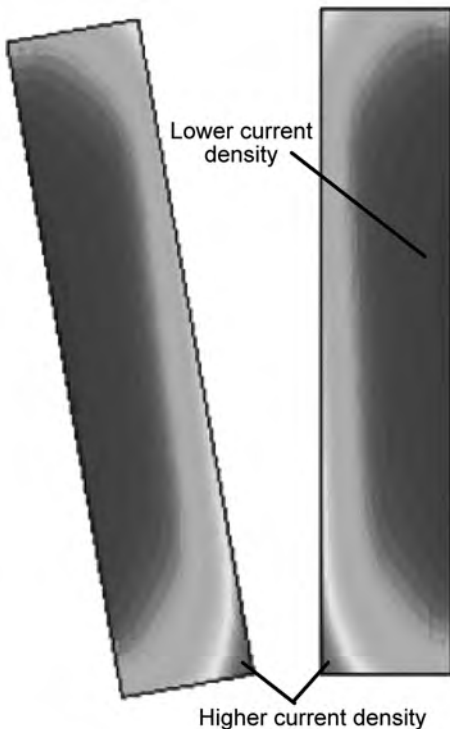


Fig. 9 Results of computer modeling showing current density distribution and the proximity effect when two bus bars have currents flowing in opposite directions. The left bus was tilted with respect to the right one, resulting in a nonconstant gap (proximity) between both bars. Significant redistribution of the current density to the region with the smallest gap can be observed. Source: Ref 22

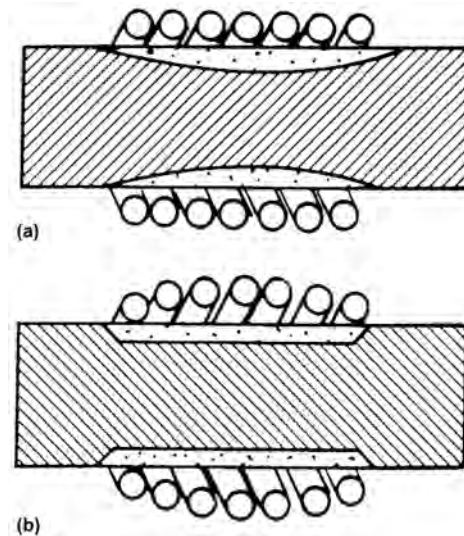
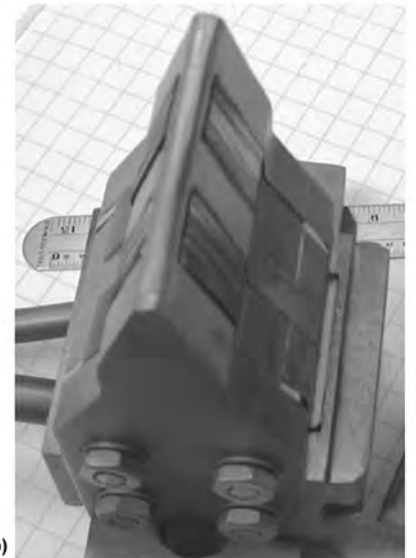


Fig. 10 Example of using a multiturn coil profile to control the heat pattern using the electromagnetic proximity effect. Source: Ref 24



(a)



(b)

Fig. 11 Examples of inductor designs that rely primarily on the proximity effect for obtaining required hardness patterns. (a) Inductor for hardening constant velocity joint races. (b) Inductor for tooth-by-tooth gear hardening. Courtesy of Inductoheat, Inc.

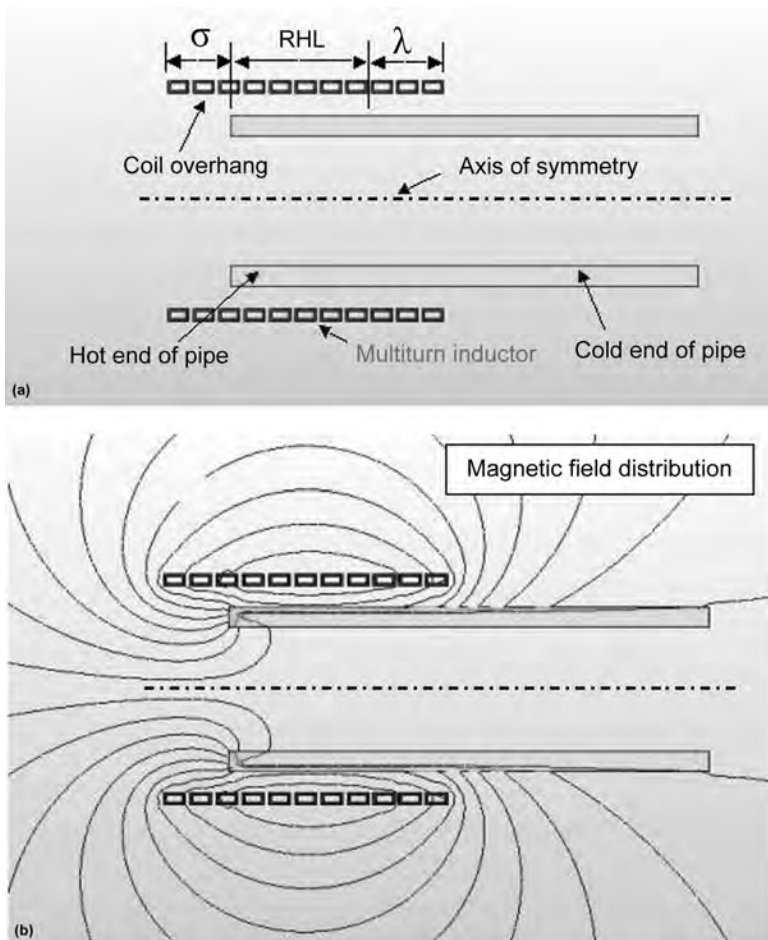


Fig. 12 (a) Sketch of the induction system for heat treating the end of a steel pipe. RHL, required heated length. (b) Magnetic field distribution when steel is below the Curie temperature

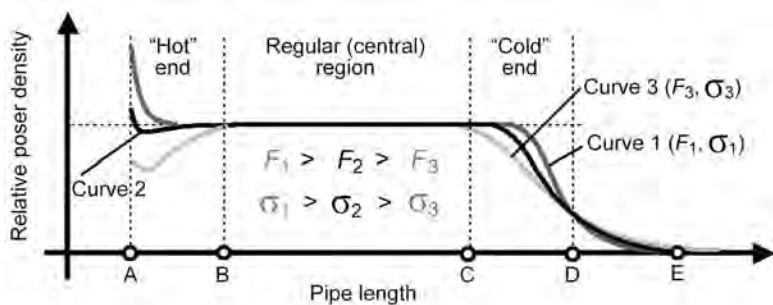


Fig. 13 Relative surface power density distribution along heated length of the pipe with three different conditions of frequency (F) and coil overhang (σ), with Curve 1, Curve 2 (F_2, σ_2), and Curve 3 as follows: $F_1 > F_2 > F_3$ and $\sigma_1 > \sigma_2 > \sigma_3$. Source: Ref 14

the required length of the hardened zone is 120 mm (4.72 in.); minimum case depth is 5 mm (0.20 in.); frequency is 2.4 kHz.

The appearance of the end effect in electrically short single-turn inductors has its own subtleties compared to multiturn coils, in particular, when high frequency is applied. Figure 15 shows an effect of relative geometrical proportions of workpiece and coil on temperature pattern in round parts using single-turn inductors and static heating mode (Ref 2, 25). This figure

illustrates a variety of cases of using single-turn solenoid coils for heating external (Fig. 15a) and internal (Fig. 15b) surfaces. Coil contouring (profiling) can help in obtaining more uniform heat patterns. In this case, an electromagnetic end effect can be compensated or suppressed by a proximity effect.

The electromagnetic end effect is also partially responsible for preheating and postheating phenomena in scan hardening. This phenomenon is discussed subsequently.

Induction-Hardening Techniques

There are four primary methods of induction hardening:

- *Scan hardening*: The coil and/or part move relative to each other. The workpiece generally rotates inside the coil to even out the induction hardened pattern around the circumference
- *Progressive hardening of elongated parts* (e.g., rods, wires, bars, tubes, etc.): Workpieces progressively pass through a number of in-line coils, similar to the heating of bars or billets prior to forging.
- *Single-shot hardening*: Neither the part nor coil axially move relative to each other, but the part is typically rotated so that the entire region to be hardened is heated all at once.
- *Static hardening*: This is similar to single shot hardening, except the part being hardened typically has an irregular geometry, which does not allow rotation.

Scan hardening can be performed on outside diameters (OD) and/or inside diameters (ID) of cylinder components as well as on flat surfaces. Both horizontal or vertical coil arrangements can be used, with the vertical design being the most popular for hardening of short and moderate-length cylinders. Some power supplies have the capability to change not only output power during scanning but also frequency.

When scanning outside surfaces (e.g., solid shafts), the induction coil typically encircles the part. A quench ring is positioned next to the coil in order to spray-quench the area that has been heated. In other cases a machined integral quench (MIQ) inductor can be used (Fig. 16). In either case, a quenching device consists of a quench chamber with numerous small holes (orifices) that allow the quenchant to impinge on the part at a specific angle and distance. As shown in Fig. 17, the induction-hardening process starts with the coil positioned at one end of the part (Ref 26). The power is turned on, the part begins to rotate, and the coil may remain stationary for a period of time to drive the heat into the part. This is known as the dwell and is typically used to preheat the fillet areas (Fig. 17a, b). The part and/or coil then begin to move relative to each other, which is why the term *scanning* is used. On some machines the coil remains stationary and the part moves, while on other machines the opposite is true.

After a short delay the quench is turned on (Fig. 17c) to quench the area heated during the dwell. The time between the first movement of the part or the coil is also called the quench delay, and it may last a few seconds depending on part geometry and hardness pattern specifics. Sometimes when the coil and/or part first begin to move, a faster speed is initially used to quickly move the coil into position so the spray will strike the area heated during the dwell. This is called the *jump-away* portion of the cycle and it is done so the area heated during the dwell does not cool down too much before