Industrial Applications of Induction Heating

There are many ways to heat metallic materials including the use of induction heaters, gas-fired furnaces, fluidized bed furnaces, salt baths, infrared heaters, electric and fuel-fired furnaces, and others. Each method has its own advantages and limitations. There is obviously no universal method that is best in all cases.

In the past four decades, heating by means of electromagnetic induction has become more popular [1–21]. The capability of in-depth heat generation in combination with high heat intensity (if required) quickly and at well-defined regions on the workpiece is a very attractive feature of this technology leading to low process cycle time (high productivity) with repeatable quality. Highly controllable heat intensities that range from moderate rates (e.g., as low as 2°C–3°C/s for tempering and stress-relieving applications) to high heat intensities (e.g., exceeding 800°C/s in gear hardening) allow the implementation of optimal process recipes/protocols.

Induction heating (IH) is also more energy efficient and inherently more environmentally friendly than most other heat sources including gas-fired furnaces, salt and lead baths, carburizing, or nitriding systems. Any smoke and fumes that may occur as a result of residual lubricants or other surface contaminants can be easily removed. A considerable reduction of heat exposure is another factor that contributes to the environmental friendliness and ergonomics of induction heaters. Advantages in safety (neither combustion nor environmental contaminants are used) in combination with low equipment cost (reduced labor cost for machine operators and improved efficiency) make electromagnetic induction an attractive investment with great returns.

IH provides much better surface quality of heated metallic materials with a significant reduction of scale and decarburization, which in turn eliminates or dramatically reduces the need for re-carburization or metal removal. The two- to fourfold reduction of scale with IH compared to heating of carbon steels using gas furnaces results in a substantial savings of metal emphasizing its cost-effectiveness.

Induction systems usually require far less start-up and shutdown time, eliminating or dramatically reducing idle periods of unproductive heating. No energy is needed to build or to maintain the heat in nonoperative conditions.

Other attractive features of IH are piece-by-piece processing capabilities with individual component traceability, high product quality, repeatability, readiness for automation, advanced monitoring, and high dimensional stability of the heat-treated parts with low distortion. In some cases, the shape distortion is so low that it allows the elimination of subsequent operations (e.g., camshaft surface hardening utilizing SHarP-C Technology may make a straightening operation unnecessary). This technology will be reviewed in Chapter 4.

Potential shop floor space savings with IH can be illustrated using the following example: induction oscillating technology for reheating large steel slabs after continuous casting may require only 10% of the floor space required by a gas-fired furnace used to provide the same production rate.
IH is a multifaceted, multidimensional phenomenon composed of complex interactions involving electromagnetics, heat transfer, materials science, metallurgy, and circuit analysis. These complex phenomena are tightly interrelated and highly nonlinear. The main components of an IH system are a heating inductor, power supply, load-matching station, water cooling and quenching (for heat-treating applications) systems, controls, bus network, and the workpiece itself.

*Heating inductor, inductor, induction coil, and coil* are all terms used interchangeably for the electrical apparatus that provides the IH effect in closest proximity to the workpiece. An inductor is often simply called a *coil*, but its geometry does not always resemble the classic circular coil shape. Figure 2.1 shows an array of a virtually endless variety of geometries of heating inductors needed to accommodate a correspondent variety of workpieces (Figure 2.2).

Inductors vary considerably not only in shape and form but also in size. As an example, Figure 2.3 shows a comparison of an Inductotherm 6000-kW/110-Hz inductor for reheating of the world’s largest carbon steel slab (maximum slab width, 3.2 m [126 in.]; thickness, 0.22 m [8.7 in.]) versus a 1.2-kW/200-kHz coil for localized heat treating of selected areas of smaller components (coil outside diameter is less than 10 mm).

Induction coils or inductors are usually designed for specific applications or for a family of similar applications. The features involved in the design and operation of IH machines...
FIGURE 2.2
Variety of workpiece geometries that routinely apply electromagnetic IH. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)

FIGURE 2.3
(a) Inductotherm 6000-kW inductor for reheating of the world’s largest carbon steel slab: maximum slab width, 3.2 m (126 in.); thickness, 0.22 m (8.7 in.) versus (b) 1.2-kW coil for localized heat treating (coil outside diameter is less than 10 mm).
greatly depend on the process specifics. Industrial applications of IH can be divided into five large groups: heat treating, mass heating, special heating applications, induction melting, and induction welding (Figure 2.4). A short description of each group is provided below.

## 2.1 Heat Treatment by Induction

The term heat treating is associated with a large family of processes. Though other materials can be heat treated using electromagnetic induction, components made of steels and cast irons represent the majority of metallic materials that routinely undergo induction heat treatment.

### 2.1.1 Hardening

One of the most common applications of induction heat treatment is the hardening of steels, cast irons, and powder metallurgy materials. Among other workpieces, Figure 2.2 includes components (e.g., camshafts, crankshafts, gears, constant-velocity front wheel drive components, transmission shafts, ball studs, pins, working surfaces of tools, and others) that are commonly hardened using electromagnetic induction developing an attractive blend of properties.

A typical hardening procedure for steels and cast irons involves heating the alloy to the austenitizing temperature range, holding it (if necessary) at a temperature for a period long enough for the completion of the formation of a fully or predominantly austenitic structure and then rapidly cooling/quenching it below the $M_s$ critical temperature when martensite starts to form. Rapid cooling allows replacement of the diffusion-dependent transformation of austenite by diffusion-less shear-type transformation, producing a much harder constituent called martensite.

Besides carbon steels, martensitic reaction is observed in many materials and its causes might be quite different. For example, martensite can be thermally induced or formed owing to the presence of mechanical stress (for example, work hardening of austenitic stainless steels in spring wire manufacturing). In cases when martensite reaction is thermally driven (e.g., attributed to intense cooling), the temperature ranges where martensitic reaction occurs and characteristics of obtained martensitic structures (including hardness, strength, ductility, and toughness to name a few) can be substantially different for
different materials. In this book, a discussion regarding martensitic reaction and obtained martensitic structures will be limited to carbon steels, cast irons, martensitic stainless steels, and some powder metallurgy materials. As-quenched martensitic structures are commonly associated with being hard, strong but having a lack of ductility and toughness and exhibiting a significant amount of residual stresses.

It should be also mentioned at this point that there are much less frequent cases of hardening when instead of forming martensitic structures, it might be desirable to form predominately bainitic or even fine pearlitic structures. For example, in contrast to the great majority of induction hardening applications, when hardening of high carbon steel rails for railways, owing to the specifics of the process requirements and safety concerns, formation of any martensite in the as-hardened structure is not permitted. Nevertheless, it is more the exception than the rule, and for the great majority of induction hardening applications, the goal is developing fully or predominately martensitic structures.

Hardening may be done for purposes of obtaining certain properties or combination of properties such as strength and wear resistance as well as the formation of a desirable distribution and magnitude of residual stresses. In some cases, it is required to harden an entire cross section of the workpiece (so-called through hardening); however, in other applications, only certain selected areas are needed to be hardened (e.g., surface hardening or hardening of a portion of the workpiece). For example, it may be desirable to obtain a certain combination of hardness, wear resistance, and contact fatigue strength at the surface or near-the-surface areas without affecting the core microstructure (e.g., hardening of gears and gear-like parts).

Other applications might require an increase of hardness and strength of the entire cross section of the part, and induction through hardening can help achieve the desirable industrial characteristics.

There are four primary methods of induction hardening [21]:

- **Scan hardening**: The coil and workpiece move relative to each other. The cylinder workpiece generally rotates inside the inductor to even out the induction hardened pattern around the circumference.

- **Continuous or progressive hardening of elongated workpieces** (e.g., bars, tubes, rods, wires, plates, etc.): Parts progressively pass through a number of coils positioned in-line or side by side. Each coil can have different power/frequency settings and mechanical designs.

- **Single-shot hardening**: Neither the part nor the inductor axially moves relative to each other, but the part is typically rotated so that the entire region to be hardened is effectively heated all at once.

- **Static hardening**: This is similar to single-shot hardening, except the part being hardened typically has an irregular geometry preventing its rotation.

Both vertical and horizontal induction hardening designs have been used by different manufacturers. Depending on the process requirements and geometry of the component, induction hardening equipment can be designed as a relatively simple apparatus with manual loading/unloading or can involve sophisticated, fully automated high-production machinery. As an example, Figure 2.5a shows a two-station CrankPro™ fully automated system for high-production heat treatment (hardening and tempering) of crankshafts [22–24].

CrankPro utilizes patented SHarP-C technology, which eliminates the need to rotate the crankshaft and any movement of the inductor during heating and quenching cycles. This
stationary heat-treating method provides several practical and technological benefits that include but are not limited to the following:

- Unique inductor design allows fully encircling main or pin journals of a crankshaft required to be heat treated (Figure 2.5b) resulting in short heat time for austenitization (typically less than 4 s). Precise, localized heating removes the need for “heat–cool” cycling, which is inevitably associated with rotational systems. This results in dramatically minimized crankshaft distortion (typically 45 μm being the maximum).
- High production rate—up to 120 parts per hour.
- Modular common base allows switching pallets for different crankshaft topology and configuration.
- Dramatically reduced maintenance cost. Coil life is at least doubled (more commonly tripled) compared to technology that requires crankshaft rotation.

A detailed description of this technology is provided in Section 4.9.4.2.

### 2.1.1.1 Surface Hardening

One of the main goals of surface (case) hardening is to form a martensitic layer on specific areas of the workpiece to increase the hardness and wear resistance while allowing the remainder of the part to be unaffected by the process [1–23]. Because of the physics of the induction phenomena, the heating can be localized to areas where the metallurgical changes are desired. Surface hardening occurs when a workpiece surface of suitable steel grade is heated to a temperature required for a phase transformation to austenite, taking into consideration the heat intensity and prior microstructure, and then rapidly quenched.

As an example, Figure 2.6 shows the dynamics of temperatures during surface hardening (heating and quenching stages) of the SAE 4340 carbon steel solid shaft (24 mm diameter) using a frequency of 9.8 kHz [17]. Minimum required hardness case depth is 3 mm and maximum total case depth is 6 mm. As can be seen, the time–temperature curves are substantially nonlinear owing to the nonlinear nature of electromagnetic and thermal physical properties (including electrical resistivity, magnetic permeability, specific heat, thermal conductivity,
heat convection, thermal radiation, and others). As can be noted, upon approaching the Curie temperature, the intensity of heating noticeably declines. An in-depth review of the nonlinear nature of the most critical physical properties as a function of temperature and their impact on the process of IH will be discussed in detail in Chapter 3.

Figure 2.6 reveals that, after 3 s of heating, the surface layer of the shaft reaches the needed thermal condition for austenization, taking into consideration the nonequilibrium nature of the phase transformation associated with rapid heating. In the case study under consideration, the heat intensity (on average) exceeds 300°C/s. Because of the short heat time, the core temperature \( R = 0 \text{ mm} \) is approximately 450°C at the end of the heating cycle (where \( R \) is radius of the heated shafts: \( R = 12 \text{ mm} \) represents the shaft’s surface and \( R = 0 \) represents its core).

The hardening inductor utilizes MIQ (machined integral quench) design where the quench device is integrated with the heating inductor (the quench system is built into the coil). Spray quenching begins practically immediately after the completion of the heating stage (though in other cases, a short dwell or soak time might be applied).

A dramatic decrease of surface and subsurface temperatures \( R = 12 \text{ mm} \text{ through } R = 9 \text{ mm} \) occurs practically instantly during spray quenching [17]. At the same time, there is a measurable time delay in the cooling of the internal regions (e.g., \( R = 6 \text{ mm} \)) and particularly the shaft’s core \( (R = 0 \text{ mm}) \). Because of thermal conduction, the core temperature continues to rise during the 2 s of quenching.

The internal regions located at a distance greater than 6 mm below the surface will not be heated above \( A_{c1} \text{ critical temperature; thus, austenite will not be formed and those regions will not be hardened. This also means that the total heat-affected zone (the region where the phase transformation occurs) will be slightly less than a distance of 6 mm below the surface, which satisfies the hardening requirement for a maximum total case depth.}

The first step in designing an induction surface hardening machine is to specify the required surface hardness and hardness pattern including the case depth and transition zone. The hardness distribution along the workpiece radius (or thickness) depends on the
following factors: final temperature distribution, thermal history, chemical composition, prior microstructure, quenching conditions, grain size, and the hardenability of the steel. The temperature distribution in surface hardening is mainly controlled by the selection of frequency, power density, and soaking (if applied), as well as workpiece-to-inductor geometry; these will be discussed in detail in Chapter 4.

Different applications and components require certain surface hardness and hardness patterns. As an example, Figure 2.7 shows constant-velocity automotive front wheel drive components that have been cut and etched to show the pattern [1]. This component requires two areas of hardening with different strength, load, and wear requirements. The “stem” needs torsion strength as well as a hard outer surface, whereas the soft core must be tough and ductile to be able to handle the mechanical shock and impact load from frequent pulsing. The inner surface of the “bell” needs hardness for sufficient wear resistance as sliding sleeve, ball bearings ride in the track or raceways. The threads of this component hold the wheel on. The thread is also hardened (using induction or carburizing) and then tempered back to produce sufficiently strong and tough thread. The tempering of these parts is nearly always done with induction, using a separate induction system.

Figure 2.8 shows a section of a complex-geometry surface-hardened shaft-like components with numerous radial and longitudinal holes, shoulders, undercuts, diameter changes, key ways, and other geometrical irregularities, which illustrate the complexity of the heat-treated components that could potentially make developing the optimal inductor...
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geometry, process recipe, and consistent hardness case depth along the entire length of the shaft very challenging.

For induction heat-treated workpieces, the cross-sectional areas of the component and the magnitude of the load they must handle determine the appropriate case depth.

Bearings, rocker arms, pump shafts, ball screws, small pins, and skid plates are examples of parts that require a shallow-hardened case primarily for the purpose of wear resistance. Hardened case depths of these parts that will enable them to handle light loads are usually in the range of 0.25 to 1.25 mm (0.010–0.050 in.). Austenization for obtaining shallow case depths requires high frequencies, short process times, and high power densities. Applied frequencies are typically within the 600-kHz to 70-kHz range.

In some cases of surface hardening of massive parts with a shallow case depth and moderate required hardness levels, it is possible to use self-quenching techniques (also called mass quenching). In cases like this, because the heated surface layer is very fine and its mass is negligibly small compared to the much larger mass of the cold subsurface area, it is possible to have sufficiently rapid surface cooling owing to heat being conducted toward the cold core. The rate of cooling might be severe enough to form a martensitic structure. The mass of the cold core acts as a large heat sink. Therefore, self-quenching can make the use of fluid quenchants unnecessary except as a cool down needed for safe handling of the part.

Components that require both wear resistance and moderate loading such as toothed racks, camshafts, and crankshafts are usually induction hardened to hardened depths of 1 to 4 mm (0.040–0.15 in.). Since the load stresses drop exponentially from the surface, these deeper case depths strengthen the part noticeably compared to shallow-hardened cases. The IH frequencies required to obtain these case depths are usually in the range of 200 kHz to 10 kHz, respectively.

Parts that must withstand a heavy load require substantially greater case depths; these include axle shafts, wheel spindles, large heavy-duty sprockets, and camshafts. In order to illustrate a typical description of capabilities of such induction systems, it is appropriate at this point to provide a short description of one such system. As an example, Figure 2.9 shows a vertical scanning precision induction hardening machine VSM-95 [24,25]. This system allows hardening cylinder shafts with lengths exceeding 2 m (80 in.) and a maximum weight of 180 kg (400 lb). To accommodate high production rates, this machine can be built as a one-, two-, or four-spindle system for optimum machine usage. The rigidity of this design results in repeatability of better than ±0.05 mm (±0.002 in.). The standard VSM-95 has a programmable logic controller–based closed-loop servo control. An individual 36-step part process program controls position, energy/power levels, dwell time, scan speed, rotation, quench monitoring, and other critical process parameters. User-selectable scanning speed is in the range of 0.5 to 200 mm/s. A suction strainer and in-line basket strainer with dual filters assures clean quench.

Heavy-load applications usually require hardness depth in the range from 5 mm to as much as 15 mm (0.2–0.6 in.) or more. Greater energy at frequencies of 10 kHz to 500 Hz and in some cases even lower frequencies are used. For example, induction surface hardening of links with bottom plates for excavators as well as track shoes for earth-moving machines often specify deep hardness case depths within the 18- to 24-mm range.

In some cases of deep hardening, a preheating cycle and multiple frequencies can be used. For example, progressive induction hardening of large mill rolls (1.2 m diameter and 20–25 mm hardened case depth) comprises two sequential stages using two inductors. The lead inductor is powered by 50 Hz and the trailing inductor is powered by 250 Hz [26].
The roll passes through the first inductor fed at 50 Hz and provides an in-depth preheating effect creating the heat barrier with respect to the cold core. Then, the roll passes through the second inductor fed at 250 Hz, which completes the austenization at the required hardness depth.

Sometimes, the heating pattern can encompass a significant part of the cross-sectional area, which, in combination with a complex geometry, may result in appreciable size/shape distortion. Where noticeable distortion is present, it may be necessary to have additional stock and case depth to allow for final grinding and polishing after hardening.

Induction surface hardening is typically characterized by high-dimensional accuracy of the heat-treated parts. The ability to keep part distortion relatively low after the heat treatment is due to the fact that IH is a very fast process and concentrates the heat generation in a surface layer needed to be hardened. The core temperature remains relatively cold, acting as a shape stabilizer. For example, an almost undetectable camshaft distortion of approximately 3–5 μm (based on 1.5- and 2.0-L diesel or regular fuel engines) is achieved utilizing the CamPro™ machine. Such low distortion allows the elimination of an entire subsequent camshaft straightening operation [22,27].

Depending on the application specifics, the heating time to complete a surface austenization often ranges from 1 to 10 s per component. At the same time, there are applications where heat time can be only a fraction of second.

Often, it is required to achieve not only a certain property of an as-hardened component but also a combination of properties that may be contradictory, for example, obtaining a combination of strength, toughness, and ductility and maximizing the formation of compressive residual surface stresses.
The complexity of the part’s geometry and the existence of holes, sharp corners, and other geometrical irregularities (Figure 2.8) can noticeably affect the design concept and hardening process recipe. The surface condition of the workpiece is another factor that can have a pronounced effect on heat-treating practice and workpiece life during service. Voids, microcracks, notches, undesirable concentration, and orientation of coarse inclusions and other surface and subsurface discontinuities as well as geometrical stress concentrators (including key ways, grooves, etc.) can initiate crack development during hardening when the metal goes through the “expansion–contraction” cycle. Thermal gradients and stresses can reach critical values and “open” notches and microcracks. In contrast, friendly microstructures with a smooth surface free of voids, microcracks, and notches make the process development less challenging and positively affect mechanical properties.

Complex-shaped components can also present known challenges in obtaining the required hardness pattern, because during heating, the “thick” sections of the part may not come up to the required temperature as quickly as “thin” sections. Thus, coil copper profiling and the use of special process settings and tooling design are needed.

In addition to that, thickness variations of irregular geometry workpieces may introduce some challenges during quenching as well, since the thinner sections or regions with holes may cool down noticeably differently compared to massive solid areas developing appreciable transient and residual stresses of substantial magnitude and requiring special adjustments in inductor design and quench device(s). All these factors must be addressed in developing appropriate designs and process recipes. For example, Figure 2.10 shows an induction machine for hardening the working surface of wrench jaws. The etched areas reveal uniform hardness patterns regardless of appreciable differences in masses adjacent to the hardened surface area. Proper copper profiling of the inductor was essential to achieve uniform hardness patterns.

When surface hardening steels, the so-called super hardness phenomenon or super hardening may be observed. This phenomenon refers to obtaining greater hardness levels in the case of induction surface hardening compared to hardness levels that would normally be expected. Section 4.1.7 reviews the potential causes of this phenomenon.

**FIGURE 2.10**
Induction machine (a) for hardening the working surface of wrench jaws (b). (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
2.1.1.2 Through Hardening

Through hardening may be needed for parts requiring high strength such as snowplow blades, springs, chain links, truck bed frames, certain fasteners (including nails and screws), and the like. In these cases, the entire workpiece is raised above the transformation temperature suitable for proper austenization and then quenched. Besides other factors, the ability of the component to be through hardened depends on the hardenability of material, quenching conditions, and geometry. The ability to achieve a sufficiently uniform through-heating is another critical factor.

Selection of the appropriate IH frequency is very important in achieving a sufficiently uniform “surface-to-core” temperature distribution in the shortest time with the highest heating efficiency. As an example, Figure 2.11 shows the thermal dynamics of through hardening an SAE 4340 carbon steel shaft (24 mm diameter) using a frequency of 6.2 kHz [17] (shaft geometry is identical to the previous case study shown on Figure 2.6). The process cycle includes 9 s of heating and 1 s of dwell/soak. As can be seen, the time–temperature curves are substantially nonlinear owing to the nonlinear nature of the electromagnetic and thermal physical properties.

The spray quench severity/cooling rate at the surface of the through heated workpiece is always greater compared to the cooling rates of its internal areas and, particularly, compared to the cooling rate at its core (assuming that there are no spray quench flow disturbances or “quench dead zones” at the surface). Thus, the steel must have sufficient hardenability in order to accomplish through hardening.

If the workpiece is thin enough or the steel has sufficient hardenability, then even a relatively modest quench intensity may provide an adequate cooling rate for internal regions of the workpiece, allowing them to “miss” the upper transformation region on the continuous cooling transformation diagram and forming the needed amount of martensite.

![Figure 2.11](image-url)

**FIGURE 2.11**
Thermal dynamics of through hardening SAE 4340 steel shaft (24 mm diameter) using a frequency of 6.2 kHz [17] (the shaft’s geometry is identical to a previous case study shown in Figure 2.6). (From V. Rudnev, Induction hardening of steels and cast irons, in *Encyclopedia of Iron, Steel, and Their Alloys*, edited by R. Colas and G. Totten, Taylor & Francis, 2016.)
within the entire cross section. A sufficiently uniform “surface-to-core” hardness distribution with insignificant hardness deviation should be obtained as a result [17].

In other cases, a greater amount of martensite may be formed in the surface and near-surface areas compared to the core. Therefore, though the hardness of the entire cross section of the heat-treated component might be substantially increased compared to the hardness of a “green” part, the hardness of the surface layers can be, to a measurable extent, higher compared to the hardness level of interior regions and, in particular, the core (assuming that the surface has not been overheated, severely oxidized, or decarburized). Such a nonuniform hardness distribution may be permissible in some applications but could be unacceptable in others.

It is reasonable to assume that in order to simplify the task of obtaining a sufficiently uniform “surface-to-core” temperature distribution in through-hardening applications, it would be advantageous to use lower frequencies that would result in more “in-depth” heating. However, there are some limitations in selection of the heating frequency. A frequency that is too low can result in cancellation of eddy currents induced by the induction coil within the part. This can result in a dramatic reduction in the electrical efficiency. Guidelines related to frequency choice and selection of other process parameters are discussed in detail in Chapters 3 and 4.

In contrast to surface hardening, where compressive residual stresses are typically formed at the workpiece surface, in through-hardening applications, the residual surface stress is often tensile.

2.1.1.3 Selective Hardening

Both induction through hardening and surface (case) hardening can be localized to particular areas of a component (e.g., ends or middle sections). This process is sometimes referred to as selective hardening. Examples of such heat treatment include the following components: valve seats (hardened zone length is within the 3- to 12-mm range), clutch pusher disk spring (length of hardened zone is 4–7 mm), levers, shifting forks, cutting edges of blades, tool joins, locking bolts, some fasteners, and so on.

Figure 2.12 shows another example of selective hardening. The hardness patterns (white color) in gears and sprockets indicate a wide diversity of induction hardening patterns obtained with variations in heat time, frequency, and power density.

![Figure 2.12](image.png)

**FIGURE 2.12**

Hardness patterns (white color) in gears and sprockets indicate a diversity of selective induction hardening obtained with variations in heat time, frequency, and power density. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
2.1.2 Tempering and Stress Relieving

The tempering process takes place after the steel is hardened, but is no less important in the heat treatment of the component. The transformation to martensite through quenching creates a hard structure. Untempered martensite is often considered too brittle for commercial use, exposing low toughness and ductility and retaining a significant amount of residual stresses.

Appreciable surface-to-core temperature gradients during the heating and quenching stages of induction hardening as well as the presence of phase transformations result in transient stresses of substantial magnitude and the buildup of three-dimensional internal residual stresses. The magnitudes and distributions of those stresses might not always be desirable and need to be adjusted by applying tempering and stress relieving.

Similar to induction hardening, tempering by means of electromagnetic induction has been found to be a viable commercial process, replacing conventional furnace/oven operations in many high-volume production applications.

As an example, Figure 2.13a shows a self-contained compact induction tempering system utilizing multiturn channel inductors to temper a variety of complex-shaped parts.

Tempering is a form of subcritical heat treatment producing an attractive combination of microstructures and mechanical properties. Some of the main purposes of tempering are to provide a desirable combination of strength, toughness, and ductility and to relieve to some degree internal residual stresses [1,2,4,12,29–31].

Reheating the steel for tempering helps relax and redistribute residual stresses. Tempering temperatures are always below the lower transformation temperature (\(A_1\)) and usually in the range of 120°C (248°F) to 650°C (1200°F). Properties of tempered steels are greatly affected not only by temperature and time at tempering temperature but also by the steel’s chemical composition and microstructure before tempering (e.g., by the amount of retained austenite as well as chemical and structural heterogeneity).

Tempering can be done in oven/furnaces (e.g., electric or infrared furnaces) or in induction systems using a batch process or a continuous process. The batch process requires that parts be accumulated after hardening and then moved to the tempering operation.

![Self-contained induction tempering system](a)

![Static system for high-temperature tempering/stress relieving](b)

**FIGURE 2.13**

Self-contained induction tempering system (a) utilizing multiturn channel inductors to temper a variety of complex-shaped parts and static system (b) for high-temperature tempering/stress relieving in the manufacture of quality connections for oil country tubular goods utilizing Patented Fluxmanager® Technology. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
Furnace/oven batch tempering is a proven process; however, it is important to consider loading conditions, making certain all parts within a load reach the proper temperature for the specified amount of time.

Induction tempering is particularly well suited to continuous processes and can be put in-line with induction hardening. Properly used induction tempering is a proven process with several operational advantages such as high production and small equipment footprint. It offers piece-by-piece part processing with in-line capability that can be very beneficial in the dramatic reduction of the probability of delayed cracking owing to minimization of the time between hardening and tempering. This feature is imperative when heat treating low-toughness materials. Because of economics, individual part traceability, and manufacturing flexibility, induction tempering has become prevalent in many applications.

At the same time, special care is needed to ensure proper results. With induction tempering, the results are achieved in a matter of seconds or dozens of seconds rather than hours. When short tempering times are applied, it is imperative to have closer control of process parameters and to assure proper part positioning with respect to the induction coil to avoid excessive variations in the tempering results.

When considering the appropriateness of induction tempering for a particular application, tempering parameters require evaluation in terms of various mechanical properties. Steels often are tempered after hardening at low temperatures, but sometimes tempering is done at higher temperatures to gain more ductility and toughness. The change in ductility may or may not be significant with a low-temperature temper. However, an improvement in ductility is only one of several factors for tempering. Tempering can also affect the yield and ultimate strength as well as the fatigue life [30,31].

The selection of equipment for tempering by means of electromagnetic induction is similar to that for induction hardening, although there are some differences. This includes the specifics of coil design, selection of process parameters, equipment for part handling, and electronic controls.

Four modes can be used with induction tempering [31]:

- Progressive or continuous tempering (Figure 2.13a)
- Scan tempering
- Single-shot tempering
- Static tempering

Case study. As an example, Figure 2.13b shows the use of a static tempering mode for high-temperature induction tempering/stress relieving in the manufacture of a high-quality connection for oil country tubular goods. This operation is typically done before machining of the thread.

In order to achieve proper stress relief of the tubes, the upset end must be uniformly heated along the entire swage length as well as through the entire wall thickness of the pipe. Axial, radial, and circumferential temperature uniformity is imperative for manufacturing quality tubular goods. Improper heat treatment could result in several undesirable phenomena from total joint failure to a type of bimetallic corrosion known as “ring-worm corrosion” that occurs in improperly stress-relieved or normalized pipes. This corrosion takes the form of a ring around the pipe usually located a few inches up from the upset.

The ability to provide uniform heating, high quality, and cost-effectiveness with space-saving induction tempering/stress-relieving machinery has been the traditional key benchmark deliverables in the past. Today, these three are joined by two additional requirements that are...
equally important: equipment flexibility and robustness. The flexibility of machinery reflects its ability to process a wide variety of parts without compromising the quality of the product.

A modern connection manufacturer can have as many as 250 different pipe diameter and wall thickness combinations to thread [358]. Pipe size diameters can vary from 2 and 3/4 in. (70 mm) to 18 and 5/8 in. (473 mm) with wall thicknesses ranging from 0.250 in. (6.4 mm) to 1.250 in. (32 mm) or even greater. In addition, the swage length can vary from 5 in. (127 mm) to nearly 18 in. (457 mm) depending on the pipe diameter, wall thickness, and application specifics. Therefore, the last (but not the least) factor is the ability to reduce downtime after changeover of induction coils while processing different products.

Robustness reflects the sensitivity of industrial machinery to withstand real-life disturbances and dimensional tolerances and provide the required performance ensuring heating quality not only under ordinary working conditions but also under extraordinary or unexpected conditions. For example, taking into consideration the diameters and overall length of the oil country and gas pipes, the necessity of processing pipes of different diameters/walls and the specifics of the real-life industrial environment, it is not unusual to have, to some degree, non-symmetrical positioning of the heated pipe inside the induction coil. Thus, it is imperative for inductor design to minimize the outcome of real-life nonperfect workpiece positioning.

The patented Fluxmanager Technology (Figure 2.13b) for pipe end heating utilizing electromagnetic induction addresses those technological challenges in the most effective manner, yielding superior temperature uniformity, flexibility, and robustness. The majority of alternative induction tempering systems were noticeably affected by relatively small deviations in pipe positioning inside of the induction coil (including longitudinal and radial positioning) producing considerable temperature gradients: radial (±ΔT_R), circumferential (±ΔT_C), and longitudinal (±ΔT_L), as well as localized “hot” and “cold” spots that could noticeably exceed permissible thermal deviations posed by industry. Fluxmanager Technology substantially improves the performance of induction tempering/stress relieving under near-life imperfections and is discussed in Section 4.6.3.2.

Different stages of tempering, microstructural specifics, the time–temperature correlation of induction tempering, and subtleties of different designs of induction tempering/stress-relieving systems are discussed in Section 4.6.3 and in Refs. [4,31,154,381,382]. Other forms of subcritical heat treatment are discussed in Section 2.1.4.

2.1.3 Normalizing

Substantially heterogeneous microstructures are produced after different steel processing operations, including casting, forging, cold drawing, rolling, and others. Re-austenization during normalizing results in nucleation and growth of new austenite grains producing upon air cooling substantially more homogeneous ferritic/pearlitic microstructures consisting of equiaxed grains. Homogenized structures are typically highly desirable for the majority of technological operations. For example, it is often suggested to normalize parts before rapid induction hardening to ensure consistent steel response to short austenization and minimizing distortion.

Normalizing of hypoeutectoid steels can be done by heating them to a temperature of approximately 50°C–100°C above the upper critical transformation temperature A_3. This ensures proper austenitization and dissolution of the majority of carbides; allowing them to be air cooled to room temperature produces fine or moderate-size grains thanks to the grain refining process.
In some cases, instead of cooling in free air (still air), forced air cooling might be specified for a normalizing operation. This is so, because the lamellar spacing of pearlite and the hardness level are greatly affected by the cooling intensity. More intense air cooling produces smaller lamellar spacing and higher hardness readings. Considerable scatter in hardness and grain size can occur when normalizing complex geometry components or workpieces having a combination of thick and thin sections. It is imperative to avoid using excessive normalizing temperatures; otherwise, several undesirable phenomena may occur including grain coarsening and decarburization.

When dealing with hypereutectoid steels, normalizing thermal conditions can be specified over a much wider range of temperatures depending on the steel’s chemical composition and the process specifics. Normalizing temperatures in this case can be noticeably below or slightly above $A_{cm}$ critical temperatures.

Not all steels can benefit equally from normalizing. For example, normalizing is not desirable for some tool steels (e.g., A2, A4, P2, P3, M2, M4, H10, H11, and H21 to name a few grades).

IH can be used effectively for normalizing elongated workpieces of small and moderate sizes (e.g., tubes, plates, and rods) made of hypoeutectoid steels. However, large-size workpieces are typically normalized (if recommended) in electric or gas-fired furnaces.

### 2.1.4 Annealing

Annealing is a broad term that is used by heat treatment practitioners to describe a variety of processes and properties related to microstructure, machinability, formability, relieving internal stresses, enhancing certain electrical properties, and the like.

Sometimes, certain corporate terms, or slangs are also used by steel processing organizations to designate particular process specifics. This includes recovery annealing (200°C–550°C), recrystallization annealing (400°C–760°C), intermediate annealing (300°C–760°C), and some others. In some instances, the term annealing has been misused in applications where the more appropriate terms should be applied (i.e., tempering, stress relieving, or stress-relief annealing).

The following are some basic groups of annealing:

- Full annealing (also commonly referred as “annealing”)
- Intercritical annealing
- Subcritical annealing (process annealing)
- Spheroidized anneal or spheroidizing

#### 2.1.4.1 Full Annealing and Homogenization

The purpose of full annealing is much like that of normalizing in that the hardness is decreased, the ductility is increased, and the material’s homogenization and some metal working properties (e.g., machinability, formability, or cold workability) are improved.

As has been shown in Refs. [28–30,32,33], full annealing temperatures depend on the chemical composition of the steel and in particular its carbon content. Full annealing temperatures of hypoeutectoid steels are just above the $A_3$ critical temperature, assuring complete austenization. Full annealing temperatures of hypereutectoid steels are just above the $A_1$ critical line representing a dual-phase austenite–cementite region.
With full annealing, time at temperature (soak time) is longer and the cooling rate is substantially slower than in normalizing, producing a softer structure that is essentially free of stresses.

Upon achieving the required thermal conditions, the steel might be either slowly cooled at a controlled cooling rate or relatively rapidly cooled to a certain elevated temperature and held at that temperature for isothermal transformation.

Typically, full annealing is done in gas or electric furnaces of two basic types: batch furnaces or continuous furnaces (e.g., roller-hearth, rotary-hearth, and pusher type).

A process often associated with a full annealing is homogenization, the major purpose of which is obtaining a homogeneous structure by eliminating alloy segregation. It is usually performed at higher temperatures than full annealing, creating favorable conditions for the diffusion-driven processes required for homogenization and dissolution of carbides. Homogenization usually occupies the temperature range of 1000°C to 1150°C.

Since such processes as full annealing and homogenization require long holding times (e.g., many hours), controlled cooling at a low rate, or the workpiece being held at an elevated temperature for isothermal transformation, the cost-effectiveness of using induction heaters for full annealing and homogenization is drastically reduced. This is the reason why IH is very seldom used in these applications. Other heat sources including gas furnaces and resistive furnaces are typically better choices.

At the same time, there is a group of applications applied for long products where induction can be effectively used. This includes heat treatment of wires or thin-wall tubular products: “black,” “dull,” and “bright” annealing of stainless steels.

Stainless steel tubing is used in decorative-type hardware, food processing, and other applications where a shiny bright appearance and low corrosion rate are desirable. Stainless steel tubing is heated by electromagnetic induction to temperatures of approximately 1050°C–1150°C and then progresses through a gas quench tunnel filled with a hydrogen–nitrogen atmosphere to prevent surface oxidation and provide a bright appearance. Of course, care should be taken for safe processing because gas mixture can be explosive owing to the presence of hydrogen in an amount greater than 4% or so.

In cases where only a nitrogen atmosphere is used, the surface of the tubes appears dull and the process is called dull annealing. Without using a special atmosphere, the tubing surface will be oxidized and the process is often referred to as “black” annealing.

**2.1.4.2 Intercritical Annealing**

In some cases, it might be beneficial to heat a steel to temperatures between the upper critical temperature ($A_3$) and the lower critical temperature ($A_1$), obtaining partial austenization (to different degrees), holding the steel at a specified temperature range followed by cooling in air or controlled cooling. This is where the term **intercritical annealing** is derived from. The final multiphase microstructure can be adjusted by changing the time/temperature/cooling rate combinations (e.g., high-strength TRIP steels consisting of ferrite, bainite, and retained austenite).

Upon reaching target intercritical temperatures and depending on the application specifics, it might be required to hold the steel at a temperature for some time. Typical isothermal holding times can vary from several dozen minutes to several hours. IH can be used for intercritical annealing when relatively short holding times are needed or as a booster heater. Whenever long holding times are required, it reduces the effectiveness of using IH systems for such applications.
**2.1.4.3 Subcritical Annealing**

Subcritical annealing (SA) (also called process annealing, recrystallization annealing or tempering) represents a large group of heat-treating processes where microstructural changes and modification in mechanical properties are achieved without austenization. Thus, the temperature range for SA is always below \( A_1 \) critical temperatures. SA represents an intermittent stage between a fully annealed condition and a cold worked condition (i.e., rolled or drawn). Work hardening takes place as a result of a cold work increasing a number of dislocations (crystal imperfections), changing a dislocation pattern, and increasing hardness. Elongated grains are often associated with a cold work.

SA helps to adjust the hardness and grain structure of steels processed on previous operations (e.g., cold-worked steels); otherwise, it might be too hard to continue cold working. Therefore, SA can be applied between certain process stages (e.g., cold-rolled low-carbon steel strip or drawn wire/rope) when steel softening is needed—this is why it is sometimes called process annealing or tempering. Transforming elongated grains into predominantly equiaxed grains, restoring toughness and ductility of steel, will improve its conditions before the next cold-work process. Several critical mechanical properties of steel (e.g., yield strength, fracture resistance, the ductile–brittle transition temperature, etc.) can be enhanced by replacing elongated coarse grain structure with fine equiaxed grain structure. An improvement in yield strength can be quantified using a Hall–Petch relation.

According to SA, a carbon steel workpiece is typically heated to temperatures of 20–200°C below the lower critical temperature \( A_1 \), held for some time at a temperature (if required), and then cooled in air or using some aqueous medium or their combination. In some cases, the needed time for holding is only a few seconds; however, in other cases, it might be substantially longer. In subcritical annealing of plain carbon and low alloy steels, softening starts with recovery that leads to a redistribution of dislocations. This process intensifies rapidly with a temperature increase.

There are two ways to implement SA of long products: box/batch SA and continuous SA. With batch annealing, a stack of rods or sheets or wire coils are heated in an enclosed furnace (e.g., resistance furnace); care should be taken to insure that internal areas of a stack are sufficiently heated.

Continuous SA can be done in furnaces (e.g., rotary-hearth or pusher type) or using induction heaters in particular when no holding time is specified or a relatively short holding time is sufficient. At temperatures suitable for SA, carbon steels retain their ferromagnetic properties, allowing extremely efficient IH of relatively thin workpieces (e.g., strips, sheets, tubes, wires, etc.) at high production rates.

Another typical application of SA/tempering using electromagnetic induction is the softening of threads of carburized components, for example, hypoid pinion gears (Figure 2.14a). Untempered carburized threads are typically too brittle and could develop a fracture during assembly or operation.

Localized SA/tempering of threads by IH allows focusing the thermal energy in the areas where greater ductility is desired without affecting the strength of the remainder of the part. Developing such a process presents several challenges to balance the thermal conditions of critical areas.

It would be beneficial at this point to review a case study. Figure 2.14b shows some of those critical areas being represented for the purpose of illustration as node “A” (fillet), node “B” (thread), node “C” (shoulder), node “D” (spline), and node “E” (core). Distance “C-D” represents an axial heat-affected zone (run out specification) that is typically within a 12- to 20-mm range. The minimum hardness readings at node “D” are usually specified...
within a 50–54HRC equivalent range. However, in order to ensure sufficient ductility and toughness, the maximum hardness is required to be approximately 42HRC (node “B”) in the threads and usually approximately 42–46HRC (unless otherwise specified) in the fillet (node “A”). The maximum core hardness is approximately 35HRC. The subtleties of this application can be described as follows:

- The thread area of the shaft (pinion stem) and, in particular, the fillet region (nodes “A” and “B,” respectively) must be heated just below the $A_1$ critical temperature to obtain sufficient softening and, at the same time, ensuring that the temperature of neighboring areas (including shoulder/diameter change) are not re-austenized nor re-hardened.
- A specific length of a “tempered–untempered” axial transition zone from the shoulder (distance “C–D”) should not be exceeded.
- The thermal conditions and process recipe should be selected to avoid or reduce the possibility of occurrence of such undesirable metallurgical phenomena as tempered martensite embrittlement and temper embrittlement.
- The location of the coil turns and copper tubing size, the process recipe, and the tooling must be optimized to obtain the appropriate 3-D temperature distribution.
- The process must be reliable and repeatable while processing a complete family of different part sizes.

Numerical computer modeling not only helps determine the optimal coil design and process recipe but also helps evaluate its robustness by estimating the impact of real-life process deviations, such as dimensional tolerances, fixture integrity, and part-to-inductor positioning.

In industrial practice, it is common to use a wide variety of inductor types and geometries. Inductor designs could comprise various numbers of turns, turn orientations (direction of current flow and current density), turn configurations (i.e., series or parallel), auxiliary electromagnetic influencers (e.g., Faraday rings, flux concentrators, flux extenders, etc.), and auxiliary thermal influencers (e.g., the bottom portion of a stem can be submerged in aqueous cooling media or be spray-quenched during the heating cycle) to reduce the extent of the heat-affected zone (HAZ).

As an example, Figure 2.15 shows the configuration of one possible induction coil for thread softening. The finite element mesh and distribution of the electromagnetic field...
in the shaft (stem) region of a hypoid pinion gear of a particular size are also shown. The magnetic field distribution indicates highly pronounced surface heating effect owing to the ferromagnetic properties of steel being heated below critical temperature $A_1$.

The inductor consists of a four-turn coil with an “L”-shaped flux concentrator applied to the lower turns. This coil design provides sufficient heating of the thread and fillet areas and is not as sensitive to part-to-coil positioning as some alternative inductor styles. The process recipe addresses the necessity to provide sufficient time at a temperature consisting of a power pulsing mode with alternations of “Power On” and “Power Off” stages. Power levels and the duration of pulses may vary from stage to stage. The pinion material is SAE 4320H steel. The frequency is 8 kHz. This type of inductor was selected because of the load tuning specifics of the available inverter used by the customer and the subtleties of the workpiece geometry. In other cases, the coil configuration might be different.
Figure 2.16 shows the results of FEA computer modeling and the temperature distribution of the top portion of the pinion stem (spline and thread areas) during the intermediate and final heating stages.

It should be noted that the fillet area is of particular concern from both electromagnetic and heat transfer perspectives. In this area, it is necessary to increase the heat intensity in the fillet because the larger metal mass produces a substantial “cold sink” effect that removes the heat from the fillet as a result of thermal conduction, and this must be compensated for by generating sufficient heating energy without re-hardening the shoulder, threads, and spline. Microhardness measurements are used to determine the hardness readings of the critical regions discussed above, including a traverse of indents at 45° in the fillet radius “A” (Figure 2.14b).

2.1.4.4 Spheroidized Anneal or Spheroidizing

Spheroidizing is a softening process that involves heating the steel to a temperature just below the lower transformation temperature $A_1$ or, in some cases, slightly above it, and holding it for a prolonged time for the iron carbide particles to assume the spheroid shape. In some cases of hypoeutectoid steels, thermal cycling slightly above and below the $A_1$ temperature might be applied to achieve spheroidization. Thus, at room temperature, a spheroidized structure represents a ferritic matrix with dispersed spheroid cementite particles. This leaves the steel in the ductile and softest possible state that can be beneficial for some subsequent technological operations such as machining or stamping.

Heating by induction is usually not the most cost-effective process for spheroidizing and full annealing, because it loses some of its major advantages such as high production rate and energy efficiency, negatively affecting the overall cost-effectiveness.

In induction hardening of steels with spheroidized prior microstructures, a longer time at higher temperature is required to obtain homogeneous austenite. Therefore, spheroidized structures are not considered “friendly” prior microstructures for rapid induction hardening.

2.1.5 Induction Heat Treating of Nonferrous Metallic Materials

Electromagnetic induction can be used for heat generation in some heat-treating applications of nonferrous alloys. One typical application is related to in-line annealing of laser welded nonferrous stainless steel (e.g., SAE 361L and 321) tubes after tube mill. Those small-diameter tubes (5–9 mm diameter and 0.25–0.35 mm wall) are used in a construction of heat exchangers. The purpose of annealing is to allow faster and more reliable corrugation and end forming of the tube in subsequent operation. After forming, welding, and annealing, the tubes are coiled at the end of the tube mill.

Another common application is induction heat treatment of light metals, which includes annealing and re-crystallization after cold working, casting, and precipitation hardening. As an example, Figure 2.17 shows a typical layout of three basket-to-basket induction annealers of ACR copper tubing [34]. Copper alloy tubes are used for water plumbing, transport, textile, industrial machinery, and consumer goods in many industries including air conditioning and refrigeration (ACR copper tubing).

The diameters of processed ACR tubing range from 7 to 12.7 mm with wall thicknesses ranging from 0.32 to 0.52 mm. Because of several advantages, induction high-speed copper tube annealing systems are replacing the older bell-type and roller hearth furnaces.

With induction annealing of copper alloys, the major savings over the roller hearth furnace occurs where the second layer winding operation is eliminated [34,35]. This not only saves the cost of the equipment purchase of a second layer winding machine but also
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reduces operating costs and provides a higher production rate. Modern induction ACR copper tube annealers can process tubes at a speed up to 600 m/min (10 m/s). The exposure to mechanical damage of fully annealed product handling is also eliminated.

Figure 2.18 shows Radyne’s induction equipment for cartridge annealing for various caliber ammunitions and munitions. The system is used to make bullets for law enforcement and military applications, as well as for hunting and shooting enthusiasts. The equipment uses a continuously fed indexing mechanism to anneal ammunition cartridges with extreme precision at a production rate of up to 320 cartridges per minute or more than 5 cartridges per second (www.radyne.com). This advanced system is capable of heat treating and
forming quality ammunition, creating specialized fragmentation patterns, specific penetration characteristics, and precise annealing profiles.

Since a heat-treating portion of this handbook concentrates on heat treatment of steels and cast irons, the specifics of heat treatment of light metals are not discussed here. Instead, a detailed description of the features of heat treating of nonferrous alloys including light metals can be found in Refs. [28,29]. Some case studies of using IH for heat treating nonferrous metallic materials will be discussed in Chapter 6.

### 2.2 Induction Mass Heating

Induction mass heating is used to heat various metallic materials to temperatures suitable for warm and hot forming (i.e., forging, upsetting, rolling, extrusion, bending, thixoforming, etc.) as well as pre-/postheating for coating operations. In many cases, the main goal is to raise the workpiece temperature to a specified level with the required temperature uniformity. This temperature uniformity may include maximum tolerable temperature differentials: “surface to core,” “end to end,” and “side to side.” A piece of stock that is nonuniformly heated may cause problems with premature wear on hammers and presses as well as problems related to excessive force to form the metal. At the same time, there are cases when obtaining certain temperature gradients is required (also referred to as gradient or profiled heating). For example, when heating aluminum billets before direct or continuous extrusion, certain thermal gradients along the billet’s length are often highly desirable.

Besides temperature uniformity, the other major goal of IH is to provide the maximum production rate at which the metallic material can be processed. High powers (i.e., from hundreds to thousands of kilowatts) and relatively low frequencies (typically in the range of 50 Hz to 30 kHz) are the most commonly used for induction mass heating. When heating relatively thin workpieces (e.g., wires, rods, plates), the required frequency can be as high as 200–600 kHz.

Additional design criteria for this type of heating include minimum metal losses (owing to scale, oxidation, burns, decarburization, etc.) and providing compact and energy-efficient systems. Other important factors include quality assurance, environmental friendliness, automation capability, reliability, maintainability, and availability of the equipment. The last criteria, but not the least, are the competitive cost of an IH system and a predictable rate of energy resources (i.e., instability of prices for gas vs. electricity) [1,2,36,37].

Although it may seem like an easy task to simply heat metallic material to a given temperature, there are many nuances of the heating schedules and process recipes/protocols that require in-depth theoretical knowledge, an extensive engineering background, and the experience of many previous jobs in order to build the optimum system to satisfy often contradictory design requirements.

The large variety of production runs (e.g., range of geometries, sizes, and alloys) to a given temperature requires careful assessment of the needed process parameters including power and frequency and their distribution along the heating line in order to optimally heat the material with the highest efficiency and system flexibility, while occupying minimum floor space.
A very important consideration is employee safety and the prevention of any type of machine malfunction that could occur while attempting to work a piece of stock that has not been properly heated.

A brief description of some mass heating applications is provided below.

### 2.2.1 Bar, Rod, and Billet Reheating

The goal of reheating is to provide the workpiece at the working stage with the desired (typically as uniform as possible) temperature across its diameter/thickness as well as along its length. In some cases, the initial temperature corresponds to room temperature. In other cases, it might be elevated and highly nonuniform (e.g., owing to uneven cooling of the bar as it progresses from the caster, its surface layers become much cooler than its core).

As an alternative source of heating, gas-fired furnaces can be used for heating bars because of the lower cost of gas at the time of preparation of this edition (2016). Regardless of that fact, bar/billet/rod producers are continuing to shift their preference toward the use of IH.

Some reasons for this shift are, first, gas-fired furnaces require a very long heating tunnel to achieve the desired temperature uniformity. The length of long products can present a great challenge in plants because of limited floor space. Also, gas firing can result in poor surface quality of metals (owing to excessive scale, decarburization, oxidation, etc.). Finally, gas heating faces ergonomic and environmental restrictions.

These factors have resulted in heating by means of electromagnetic induction becoming the preferable choice to reheating bars, billets, and rods of both ferrous and nonferrous metals (Figure 2.19). The Inductotherm Group has supplied several hundred Inductoheat Group bar/billet/rod heaters of various types to the metal warm and hot working industry worldwide. Power ratings of these machines vary from less than 50 kW to more than 20 MW.

Depending on the specifics of the application, an induction bar heating system may consist of one or multiple in-line induction coils powered by several inverters that have different frequencies and power ratings. In some cases of high production of large-diameter steel bars, a heating system can consist of more than 30 coils in-line.

Depending on the application specifics, heat uniformity, and market needs, there are a variety of electrical circuits and coil connections that are used by different manufacturers.

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**FIGURE 2.19**

IH is traditionally used to heating bars, billets, and rods made of ferrous and nonferrous alloys before warm and hot working. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
In some cases, coils could be connected in series or parallel depending on the type of power supply (e.g., voltage source or current source), or coils could be connected in some combination of series and parallel tuning. The choice of coil connections is often related to the type of power supply, its load matching capability, and the necessity to avoid reaching the power supply output limits.

A single large power supply or multiple smaller power supplies can be used. In many cases, a modular design concept (e.g., Inductoforge Technology) could maximize the advantages of IH and provide the desirable combination of the highest heating quality and the maximum process flexibility.

The challenge in IH of bars and billets arises from the fact that the surface-to-core temperature profile continues to change as the workpieces passes through the line of induction coils. Because of the physics of the process (as reviewed in detail in Sections 6.1.5 and 6.2); the core tends to be heated more slowly than the surface. At the same time, the leading and trailing ends have a tendency to heat differently compared to the middle section of the body of the bar in cases when bars are not processed end to end.

Billets are shorter pieces of bar stock that have been cut off for individual handling. The billet may be heated to forging temperature and fed into a forging press or hammer. The result at the end of the forming process is a part with a small amount of residual metal that must be trimmed away to yield the final forged part. As an example, Figure 2.20 shows a variety of final forged products made from billets that have been induction heated before the forging operation.

Billets typically move through the induction heater using (depending on the application specifics) continuous or incremental pushing systems, conveyors, belts, or walking beam systems, which allow processing the billets through the induction coil.

The diameters of the steel billets and bars usually vary from 12 mm (1/2 in.) to 250 mm (10 in.). However, the diameters of nonferrous billets can be much larger. For example, it is not unusual to induction heat aluminum and titanium billets of diameters of 450 mm (18 in.) and larger.

In some applications, obtaining a uniform heat distribution is not desirable and certain longitudinal/axial temperature gradients are specified. For example, depending on the particular aluminum alloy and the specifics of the extrusion press, the temperature of the leading end of the billet might be specified approximately 40°C–80°C higher than its trailing end. This type of thermal gradient helps achieve close to isothermal extrusion conditions of the taper-heated billet being extruded at a constant ram speed, which positively affects the quality of extruded aluminum products. Figure 2.21 shows three side-by-side “flying-loader” noncontact dynamic taper aluminum billet heaters (billet O.D. = 250 mm).

FIGURE 2.20
Variety of steel forged parts made from billets that have been induction heated before the forging operation.
These systems allow developing accurately controlled longitudinal thermal gradients that are highly desirable for direct extrusion of aluminum billets. Target temperatures depend on the alloy grade and application. For example, for steels, the final temperatures before hot working normally vary from 1050°C (1922°F) to 1260°C (2300°F). For aluminum billets, final temperatures are usually in the range of 480°C (896°F) to 580°C (1076°F). Temperatures of 900°C (1652°F) to 1000°C (1832°F) and 950°C (1742°F) to 1050°C (1922°F) are typical temperatures for heating copper and titanium billets, respectively. At the same time, temperatures outside of these ranges can also be specified to suit particular application specifics.

Instead of heating the entire billet or bar, another common approach is to heat certain portions of the workpiece (e.g., its ends or middle area) to elevated temperatures for a subsequent operation (e.g., a press or hammer to form the end of the bar into the desired shape or bending machine). As an example, Figure 2.22a shows a compact three-position induction system for heating selected areas of carbon steel bars to temperatures in the forging range. End heating of steel bars using (a) three-position solenoid-style heater and (b) channel-type inductor. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
range. Figure 2.28 illustrates a channel-type inductor for heating bar ends permitting easy entry and exit. Bars are continuously processed side-by-side.

Another example that illustrates the unique capability of IH to heat selective areas of the workpiece is applied in the manufacture of large crankshafts such as those utilized in marine main propulsion engines that can exceed 20 m in overall axial length and weigh in excess of 300 tons. A large crankshaft comprises a series of crankpins (pins) and main journals (mains) interconnected by crank webs or counterweights. The diameter of the journals can be as small as 75 mm (3 in.) and can exceed 305 mm (12 in.). Large crankshafts are heated and hot formed, for example, by a hot rolling or forging process, which is favored over rolling. Steel forgings, nodular iron castings and microalloy forgings are among the materials most frequently used for large crankshafts. Forging temperatures used for steel compositions can range between 1100°C and 1300°C. Exceptionally high strength, sufficient elasticity, good wear resistance, geometrical accuracy, low vibration characteristics, and reduced cost are important factors in the production of large crankshafts [38].

The massive size of those crankshafts does not permit forging of the entire crankshaft at one time, as is done, for example, with smaller crankshafts used in internal combustion engines of automobiles. The feedstock or blank used in the process is typically a drawn cylindrically shaped blank at ambient temperature.

An attempt to selectively heat such a massive workpiece in gas or resistance furnaces is highly ineffective, extremely time consuming, and, in many cases, simply not feasible because of the cost. The selective heating capability of electromagnetic induction makes this application realistic and cost efficient.

According to one IH design, initially, a first pre-forge section of a blank is positioned within the induction coil and heated. Upon achieving the desired temperature in the respective section, the blank is transported to a forging press to forge the appropriate crankshaft feature, such as a first main journal or pin.

Subsequent to forging the first journal, the entire blank is cooled down to near-ambient temperature. The second pre-forge section of the blank is then positioned within the induction coil to heat the next section to forge temperature. Similar to the process for the first pre-forge section, the second pre-forge section is forged as the second journal, after which the entire blank is again cooled down before heating the next section of the blank for forging. The process steps of section heating, section forging, and blank cool down are repeated for each subsequent feature of the large crankshaft.

Cool down of the entire blank after each section forging is driven by the necessity of having the same initial thermal conditions throughout the longitudinal length of the next section to be pre-forge heated so that the IH develops the needed thermal conditions (including sufficiently uniform longitudinal and radial temperature throughout) for the next section. Without the cool-down step, heat from the previous forged section will axially flow by thermal conduction into the next section(s), creating a nonuniform temperature distribution profile across the longitude of the next section, which will result in a nonuniform temperature distribution profile across the length of the next section after it is inductively heated within the induction coil. These cool-down steps are both time consuming and extremely energy inefficient since heat energy dissipation to ambient in the cool-down steps of such massive workpiece represents a nonrecoverable heat loss. Consequently, the overall energy consumption is dramatically increased with a substantial reduction in the overall process efficiency.

Thanks to advanced knowledge related to the effective control of electromagnetic end effects and the capability of IH to precisely control electromagnetic end effects redistributing heat generation depending on the initial 3-D temperature distribution, successive IH
and forging of shaft components can be accomplished without cool down between the heating and forging steps by sensing the actual temperature distribution along the axial length of the next section of the shaft to be inductively heated and forged [38].

The temperature profile obtained as a result of previous “heating-forgiving-transporation” stages is used to adjust the heat generation along the length of the next section so that the required (e.g., sufficiently uniform) temperature distribution along the axial length is achieved before a subsequent forging. The monitored temperature profile data from a forged shaft workpiece may be used to adaptively adjust the amount of electromagnetic heating power along the length of the next shaft workpiece to be forged [38].

Corresponding sections of Chapters 3 and 6 provide a detailed discussion with respect to various electromagnetic effects, including end effects.

### 2.2.2 Thixoforming Applications

Some metallic materials (including but not limited to aluminum and magnesium alloys) can be heated to a partially liquid state in order to easily form the slug into the desired final complex shape, achieving a low level of product porosity without entrapment of gas and also providing high flow viscosity during casting. This process is called thixoforming or semisolid casting.

Target temperatures are very close to the melting point of the particular alloy, and if the temperature is slightly higher than required, the slug can collapse into a puddle of liquid metal or sag into the support structure. The heating is continued until the slug is partially liquid (usually 50% solid and 50% liquid), but held together by the slightly cooler outer oxidized surface layer that has higher liquidus temperature compared to pure metals or nonoxidized alloys. The quality of semisolid casting is greatly affected by the ability to achieve the needed temperature uniformity within the slug. IH has been identified as the process that best meets the heating criteria for semisolid forming. There are two different types of induction coil arrangements: vertical and horizontal. Automated systems control the temperature very closely (typically within ±3°C) and usually involve multiple billets in process and a subtle coil design that will be discussed in Section 6.5.

### 2.2.3 Tube, Pipe, and Vessel Heating

There are many heating applications for tubular products including annealing, normalizing, stress relieving, hardening, heating before sizing, piercing, parting, coating, bending, remelting of surface metallic spray coating, and so on. The heating of tubes, pipes, and other hollow workpieces is somewhat different from the heating of solid bodies.

With a solid workpiece, there is considerable conduction of heat toward the colder core or center of the heated workpiece. Besides, there are no heat sources generated in the core regardless of the selected frequency when using solenoid-type coils, which are the most popular designs.

With a hollow workpiece, under certain conditions, there could be generation of heat sources not only on the outside diameter but also on the inside diameter. When the wall of a heated tubular workpiece is relatively thin compared to the eddy current penetration depth, the reflected impedance of the load and electrical efficiency at a given frequency can be much different. These features make a marked difference in choosing the process parameters and design of the IH system for tubular products; these are discussed in Section 6.7.
2.2.4 Wire, Rope, and Cable Heating

The extensive use of IH for heating wire, rope, and cable products in such applications as heat treatment, coating, thermal diffusion, drying, plating, encapsulation, stress-relieving, relaxation, and others demands a wide range of process concepts. It is advantageous to use continuous feed-type systems when processing long workpieces. In these cases, an IH system often utilizes an oval bore coil with multiple openings and individual guides for multiple wires to pass through. The ceramic tubes/guides allow the surface heat loss to be minimized and somewhat assist with mechanically constraining the movement of the wire.

As expected, the maximum electrical efficiency would be associated with the tight inductor-to-wire coupling. However, wire processing often requires appreciable gaps for safe part processing.

Since the wire is relatively small in diameter, it loses the induced heat quite quickly because of a low volume-to-surface ratio and relatively high thermal radiation and forced heat convection from the surface. Frequencies in the range of 10 to 800 kHz are applied with wires traveling through the inductor at speeds as high as 2 m/s and even higher. As an example, Figure 2.23 shows Radyne's induction heat treatment line for the hardening and tempering of 1060 carbon steel spring wire in the diameter range of 4 mm (0.162 in.) to 8 mm (0.312 in.) using a dual-frequency design concept (www.radyne.com). Heating below Curie temperature is carried out using a 400-kW/10-kHz inverter. A 420-kW/200-kHz inverter provides heating above the Curie temperature. Tempering is also carried out by means of electromagnetic induction.

Often the requirements of wire processing demand the use of a protective atmosphere that can be easily incorporated into an IH system.

A variety of process features and physical phenomena that distinguish IH of multiple wires, cables, ropes and small-diameter tubes from conventional IH of solid cylinders, bars, and even single wire heating are discussed in Section 6.6.

FIGURE 2.23
Radyne's induction line for the hardening and tempering of SAE 1060 carbon steel spring wire in the diameter range of 4 mm (0.162 in.) to 8 mm (0.312 in.) using a dual-frequency design concept. (Courtesy of Radyne Corp., an Inductotherm Group company.)
2.2.5 Slab, Plate, Rectangular Bar, and Bloom Heating

Slabs, plates, and blooms of various geometries may be heated and later rolled down to the final desired size. Some of these are cooled and later reheated for rolling or forming; others are reheated as a part of a continuous process to facilitate the subsequent rolling or forming operation. These types of systems utilize high powers of low and medium frequency (depending on the thickness and alloy) and often multiple coils. Figure 2.24 shows an Inductotherm system for heating the world’s largest steel slab (3.2 m wide and 0.22 m thick) that provides reheating of a single large slab or smaller-size twin slabs.

When heating rectangular-shaped workpieces, the difficulty in obtaining heat uniformity is associated with appropriate control of “skin” effect, electromagnetic longitudinal end effects, electromagnetic transverse edge effects, and thermal edge effect. If the initial temperature of the slab or bloom is uniform, then in order to provide a uniform temperature distribution within the slab, it is necessary to ensure a balance of these phenomena.

There are several different inductor arrangements available to heat slabs by induction; however, the great majority of applications apply longitudinal flux coils (rectangular solenoids). Depending on the process requirements, there are several main design concepts of induction slab heating systems: static heating, in-line progressive/continuous heating, and oscillating heating.

Frequently, the initial temperature distribution within the cast ingots, slabs, or blooms is nonuniform, having a complex temperature profile before reheating by induction. Among other factors, the specifics of temperature nonuniformity depend on the geometry, the specifics of cooling during previous operation (e.g., the casting), and the production rate. Obviously, there is substantially much less energy required to reheat the slabs from intermediate thermal conditions compared to the case when the slab is completely cooled down to room temperature. However, the intermediate thermal conditions complicate the system design tremendously, resulting in the necessity to select a process schedule/recipe (including frequency) based on the specifics of the initial temperature distribution. Slab edges tend to cool faster than the central areas and, in particular, its core. Therefore, it is

![FIGURE 2.24](image_url)

*IH system for heating of the world’s largest carbon steel slab. (Courtesy of Inductotherm Corp.)*
often required during reheating to intentionally nonuniformly distribute generated heat sources within the slab in such a way as to properly address its nonuniform initial thermal conditions.

Special control means are required to monitor and predict the incoming temperature profile and to adjust the power level of the heater to maintain a sufficiently uniform output temperature.

Section 6.8 is devoted to a discussion of the major features of IH of rectangular bodies with uniform or nonuniform initial temperatures.

2.2.6 IH of Strips, Thin Slabs, Plates, Films, and Sheets

There are a variety of applications that require the heating of thin flat workpieces (e.g., metallic sheets and strips) that are fed in a continuous fashion. Heating of those workpieces might be needed before coating the sheet with a protective layer, curing of paints and varnishes, or annealing, pickling, or thermal spraying. Tight temperature control with sufficient heat uniformity across the width of the strip is imperative to ensure product quality.

IH of strips, plates, thin slabs, and sheets has many similarities compared to the heating of large-size slabs and blooms. At the same time, there are some unique features.

There are five basic induction strip heating inductor designs: longitudinal flux coils, transverse flux inductors, traveling wave inductors, channel-type coils, and “C”-type inductors.

Heating of ferrous materials at lower temperatures commonly require using relatively low frequencies. At higher temperatures (i.e., above the Curie point), in order to provide high efficiency and the ability to reach target temperatures, higher frequencies are needed. In some cases, it is necessary to change the direction of the magnetic flux in the workpiece to achieve better efficiency at higher temperatures when heating thin nonferrous products (i.e., transverse flux inductors or traveling wave inductors vs. longitudinal flux coils).

There are two major concerns faced by the designers of induction machinery for strip heating. One of them deals with the ability to provide temperature uniformity across the

FIGURE 2.25
Radyne Field Joint Heating and Merlin Coating Systems deliver an efficient means of IH and coating field joints by carrying out both operations simultaneously. Radyne Offshore Clam Coil systems are designed for use in offshore pipe-laying applications and utilized for a number of pipe heat treatment tasks. (Courtesy of Inductotherm Heating & Welding Ltd., UK, an Inductotherm Group company.)
strip width. The ability to avoid eddy current cancellation and obtain high coil efficiency when heating nonmagnetic thin strips is another concern.

Because the strip might be moving at a fast rate, large power supplies are needed to provide the required energy input in order to guarantee the desired production rate. Section 6.9 discusses the intricacies of IH of strips, plates, sheets, and thin slabs.

2.2.7 Coating

IH of wires, strips, and tubes has been used for a variety of applications involving the coating, spraying, and curing of various coatings such as paints, varnishes, and zinc alloys for galvanizing steel, for example.

Figure 2.25 shows Radyne Field Joint Heating and Merlin Coating Systems delivering an efficient means of IH and coating field joints by carrying out both operations simultaneously. Radyne Offshore Clam Coil systems are designed for use in offshore pipe-laying applications and have been utilized for a number of pipe heat treatment tasks. Field Joint Coating Systems apply a precise two-coat FBE and copolymer coating, delivering vastly improved cycle times and quality, fully automated precision control, and minimum manning levels. Multiple coating heads provide a faster, more uniform coating compared to alternative designs. The benefits of the Merlin system have been proven on several international pipeline projects (www.inductothermhw.co.uk).

The coil is manufactured in a nonconductive composite frame to support the water-cooled coil wraps with an over center clamp to manually clamp the clam-type coil around the joint area. For larger pipe diameters, it supports pneumatic automated operation.

Low-temperature pyrometers and associated electronics are also included. The pyrometers measure the surface temperature of the steel pipe before the application of the FBE coating. Once the surface has reached a predetermined temperature, the pyrometer triggers the FBE coating process.

2.2.7.1 Curing of Paints and Varnishes

Curing of paints and varnishes (drying/evaporation or polymerization) on surfaces of strips, sheets, wires, or curing powder coating materials (e.g., used in thread patching of fasteners) requires special design considerations related to ensuring the quality of curing and avoidance of uncontrolled overheating. In addition, when curing some paints and varnishes, there might be the potential for a fire if a spark occurs. Surfaces must be properly prepared to ensure that the coating will adhere to the base metal.

Induction curing system for fastener patching applications usually applies a channel-type or split-return inductor and often comprises two coil arrangements. The first inductor is relatively short, allowing preheating of selective areas of continuously processed fasteners before spraying. The second inductor provides suitable final thermal conditions, ensuring proper powder flow after spraying.

Because IH generates the heat within the metallic material located below the paint or coating (the substrate), the heat flows inside to outside, allowing any outgassing without pinholes. The mechanical movement of the painted surface must be constrained and the heating coil opening should be sufficient to allow adequate clearance for the painted workpiece (e.g., strip) to move within limits without physically touching any solid surfaces and avoid surface damage until the process of curing is completed.
During the process of evaporation, the fumes should be removed properly and care must be taken to ensure that aqueous residuals and condensed water do not excessively accumulate above the processed strips and drip on the as-cured surfaces.

Since the curing requires low temperatures, carbon steels retain their ferromagnetic properties and the heating can be done cost-effectively using relatively low frequencies even for thin strips. High power levels allow fast heat generation for curing, often resulting in a fraction of the needed shop floor space compared to conventional ovens. Lengthy “warm-up” and “cool-down” cycles are avoided with IH.

### 2.2.7.2 Preheating before Thermal Spraying

Thermal spraying involves the application of a coating material to the workpiece surface heated to an elevated temperature. The material adheres to the surface of the metal or metallic alloy that it is sprayed on and provides a cost-effective way to increase resistance to wear, corrosion, and heat. Electric arc combustion and plasma spray coating can be used.

Spray coating can be applied to a motionless workpiece or onto a moving part. In some cases, a stationary inductor and spray system is used while the workpiece moves continuously through the induction line. In other cases (e.g., for coating sections of pipes), systems have been designed utilizing a moving inductor along a stationary workpiece. A spray head, mounted very close to the moving inductor, applies the coating material on a preheated surface.

### 2.2.7.3 Galvannealing, Galvanizing, and Galvaluming

The hot dip coating of carbon steel with zinc and or aluminum involves the process of feeding a continuous steel strip through a variety of different stages to clean and prepare the material, anneal, coat, cool, inspect, and finally to apply a protective coating before storage.

Galvannealing is the continuous annealing of the steel strip after the dipping of the strip, wire, or tube into a molten zinc or zinc–aluminum bath. The strip temperature is raised to the point of remelting the zinc, which leads to the formation of particular zinc–iron alloys.

![Continuous galvanizing line of low carbon steel strips that includes solid-state power supplies, induction melting pot, and an induction strip heating system. (Courtesy of Inductotherm Group.)](image-url)
This coating facilitates uniform appearance and adhesion of paints as well as electrical welding of the strip when used in the automotive industry.

Galvanizing is the continuous process of coating the strip by transporting it through a molten zinc bath. As an example, Figure 2.26 shows a continuous galvanizing line of low carbon steel strips that includes solid-state power supplies, induction melting pot, and an induction strip heating system built by the Inductotherm Group.

A patented doorless inductor design provides several measurable advantages including an ability to withstand the adverse effects of zinc dust and to eliminate the need for frequent and costly maintenance of the door contacts, allowing for easy movement of the inductor online/offline and reducing time and the cost of commissioning since the unit is preassembled and tested in the workshop.

Galvaluming is a coating process similar to those previously discussed but using coatings composed of zinc and various percentages of aluminum. The aluminum content helps make the material more malleable during the continuous folding of the strip on the various rollers. Some coating jobs require a pure aluminum coating.

Virtually instantaneous changes in heat generation intensity of IH allow accommodating required variations in speed/temperature/materials with a minimum yield loss.

2.3 Special Applications of IH

There are a large number of special applications where IH can be used quite effectively in a broad base of different industries. Some of these are described below.

2.3.1 Joining, Friction Welding, Brazing, Bonding, Soldering, and Sealing

When joining and bonding different metallic pieces together, it is very common to apply electromagnetic induction as a heat source. An example of induction joining would be the heating of the end of an axle hub before it is friction welded by spinning it at high speed and pressing it against the end of the axle housing or induction bonding of a car vibration...
damper assembly that typically comprises different materials needed to be bond together. Chapter 5 provides a thorough discussion on induction joining applications and process specifics.

Brazing and soldering are also typical induction joining applications. In these processes, two pieces of metallic materials are held sufficiently close together and heated to an appropriate temperature. A flux is applied to the joint to prepare the surface and enhance the flow of the brazed material (called “filler”) or solder into the joint. Precise temperature control is essential and the gap between the two pieces to be joined together is critical for achieving a successful joint (see Section 5.1). Figure 2.27 shows induction machines for a combined hardening and brazing operations of the working tips of tool bits for the mining industry.

In addition to brazing and soldering, bonding is another popular approach to joining two or more materials. In contrast to brazing and soldering, in bonding applications, components being joined do not have to be metallic. One of those components being metallic (even if others are nonmetallic) might already be sufficient. In bonding applications, the effect of bonding is provided by an adhesive. Most adhesives are not electrically conductive material and cannot be directly heated by electromagnetic induction. This is the reason why at least one of the joining components should be electrically conductive and capable of being heated by induction. Induction bonding has been done successfully for joining a variety of different components and shapes and is discussed in Section 5.2.

It is common to use IH to cure an epoxy or thermal setting glue that is used to bond different sections of sheet metal. The bond can be a complete seal around the periphery of the component (e.g., panel) or it can involve spot bonding, where the panel is fastened at a number of discrete locations around the periphery rather than a continuous loop. This process can be used to bond metal to metal or metal to nonmetallic material.

A single power supply can be used for continuous bonding, whereas a number of small individual power supplies may be used for spot bonding. The advantage of individual power supplies is that they provide individual control of the temperature at each bonding point rather than attempting to control the temperature at individual points by contouring the inductor or using flux concentrators.

2.3.2 Shrink Fitting and Disassembling

A common application of IH is the heating of various types of housings and base assemblies for insertion of another component, such as a shaft or a pin, into a properly sized hole. The base assembly with a mating hole is typically heated to approximately 200°C with low frequency to ensure uniformity of the heating and expansion in the desired area. When the area around the hole has been heated to allow the size of the hole to increase as the metal expands, a pin is inserted freely or sometimes with a small amount of pressure to press it into the hole to mate with the base assembly.

A typical assembly of this type would be an automotive steering knuckle, which has a wheel spindle inserted into the hole in the knuckle. Another common use of shrink fitting is for the insertion of bearing assemblies into a parent housing.

In shrink fitting, sufficient mass around the hole must be heated for the size of the hole to increase. If local heating is done inside the hole using I.D. inductors for a short time, the reverse effect may be seen and the metal may expand in the direction of reducing the hole diameter and preventing the insertion of the pin or bearing assembly.
Disassembling is the reverse process to shrink fitting and IH can be applied here as well, for example, motor frame heating for disassembly when open frame motor posts are heated to soften the epoxy. This enables the motor frame to break apart and the parts to be salvaged.

### 2.3.3 Motor Rotor Heating

In the past, ovens and furnaces have been widely used for rotor heating applications. However, at this point, the heating by means of electromagnetic induction dominates this market. There are several reasons why manufacturers of small- and moderate-sized rotors have turned to IH.

Fossil fuel–fired, resistance, or infrared ovens and furnaces can consume valuable floor space; negatively contribute to working environments; and involve large quantities of products in a workflow. Start-up, shutdown, and, in some cases, product changeover might be time-consuming and costly.

In the production of small- and moderate-size motors (Figure 2.28a,b), IH is used for a variety of applications, including the following [39]:

- Die-cast aluminum bond breaking (thermal shocking) to improve electrical efficiency
- Lamination bluing for rust prevention and an increase of electrical resistivity between lams, which is associated with a correspondent efficiency increase
- Rotor heating for motor shaft insertion and shrink fit assembly (Figure 2.28b)
- Epoxy curing for component assembly; curing epoxy used in the assembly of stator in housing and also for field ring magnet bonding
- Varnish curing
- Hardening of motor shaft bearing surfaces
- Preheat for die-casting
- Heating for wire stripping and others

![IH applications](https://example.com/ih-applications.jpg)

**FIGURE 2.28**
IH is applied for various processes associated with a production of small- and moderate-size motor rotors (a). IH is used for motor shaft insertion and shrink fit assembly (b). Small rotor heating requiring only 3 kW of power (c). 100-kW/1-kHz induction rotor heater (c) for heating rotors with diameter ranges from 57 mm (2.25 in.) to 115 mm (4.5 in.). (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
As an example, Figure 2.28c shows a 100-kW/1-kHz in-line induction rotor heater consisting of an adjustable load magazine, electric actuator charge system with watercooled charge lance, solenoid-type encapsulated heating coil, rotor up-ending device, pick and place unit, operator shaft drop location with automatic motor shaft positioner, and spray quench cool-down system. This induction system provides heating of rotors up to 510°C (950°F) at a production rate of 240 rotors per hour. Rotor diameter ranges from 57 mm (2.25 in.) to 115 mm (4.5 in.), and stack height ranges from 16 mm (0.63 in.) to 155 mm (6 in.).

IH of motors provides a number of attractive features compared to alternative heat sources (e.g., ovens) that have been reviewed in Ref. [39] and Section 5.5.

2.3.4 Seam Annealing

In the manufacture of tubular products, it is often necessary to form the tube from a piece of flat metallic strip or plate. A seam occurs at the point where the two ends of the strip meet to form the cylindrical shape of the tube forming a straight longitudinal or spiral seam. This seam is usually welded to form a tubular product. Unfortunately, welded seams typically exhibit heterogeneous microstructures that are associated with high brittleness, poor toughness, and being prone to cracking. In order to prevent brittleness at the welded joint and improve the microstructure, the tube can be full-body annealed or only the welded area can be selectively heat treated.

Common types of inductors used to selectively anneal the longitudinal seam of pipes and tubes are split-return and butterfly-type inductors. These types of coil arrangements provide high field strength in the joint area. Flux concentrators (laminations) assist to further focus the heating in a narrow band along the welded seam providing the needed heat-treating effect (see Section 4.2.3.1).

2.3.5 Induction-Assisted Laser Materials Processing

Electromagnetic induction can assist other thermal technologies including laser processing. Because of the nature of lasers, high intensity heat sources are generated, producing high temperatures, significant thermal gradients, transient and residual stresses, worsening ductility, toughness, and some other mechanical properties. In addition, unwanted microstructures and undesirable hardness increase often occur (attributed to a combination of high temperatures and the intense mass cooling rate). Induction pre- and post-heating may assist in a noticeable reduction or elimination of some of those drawbacks.

A nonexclusive list of applications where IH may assist laser processing includes but is not limited to the following:

- Induction-assisted laser welding and weld-based additive manufacturing
- Induction-assisted laser surface remelting
- Induction-assisted laser cladding
- Induction-assisted laser hardening, and others

IH before or after laser processing can help reduce thermal gradients, improve distribution of stresses and industrial characteristics of products, eliminate cracking, and produce desirable microstructures [40].
2.3.6 Food Industry

A variety of applications of IH are found in the food industry. Many systems utilize susceptors that are heated by induction and transfer the heat to the food by conduction, heat convection, or thermal radiation. Induction food warmers and induction stoves work by this principle. Induction extruders are used to produce many types of grain transformation and confectionery products. Large cauldrons are used for cooking caramel and other similar products and there are also fluid heating systems used in the production of milk and some beverages. Heating of rollers used to make thin products such as pizza, pie dough, and cookies are among other applications related to using IH in the food industry.

In recent years, induction cookers (e.g., rice cookers) gained their popularity in a number of countries. Instead of heating cookware by flame or by heat transfer from resistance heating elements, electromagnetic induction provides heat generation within the cooking vessels, resulting in faster, better controlled, and more energy-efficient heating.

2.3.7 Papermaking

In the papermaking industry, IH is used for heating of calendar rolls to accurately control the thickness and quality of the paper produced. A variety of individual coils are spaced along the length of the calender roll. The roll temperature and paper quality are continually monitored and the power levels are adjusted accordingly to provide the desired temperature at each point along the length of the roll.

2.3.8 Wool and Wood Processing

It is possible to utilize IH in industries that require the drying of materials as they pass along a production line or in batches offline. The induction coil is used to heat a metal plate, which in turn may contact the material and heat it by conduction or convection.

2.3.9 Chemical Industry

In the chemical industry, IH is used to heat various types of reactors and distillation equipment, which is used in the production of pharmaceutical products and steam makers or in waste treatment operations. In most induction systems, the inductor copper losses that result in water heating are considered to be an undesirable by-product of the IH process. In the chemical and food industry, it may itself be the desired end product required to be maximized, fabricating an inductor from material that exhibits high electrical resistivity such as stainless steel, for example. Some of the benefits of using electromagnetic induction in such applications as opposed to open flame heating are ease of control, safety, and efficiency.

2.3.10 Cap Sealing

Cap sealing is an important application in the food and pharmaceutical industries. Concern, with respect to illegal tampering with food or drugs before consumer use, has led to the development of cap sealing technology.
This technology provides consumers with a comfort that the product they are using is coming to them in exactly the same form and purity in which it was packaged at the factory.
With this process, a small layer of aluminum foil is placed on the top of a container that has been filled and inspected. The container with the foil is passed under an induction coil, which heats the foil to a sufficient temperature to bond it to the top of the container. The contents are thus sealed and virtually guaranteed safe at the point of final use (see Section 5.3).

2.3.11 Miscellaneous
Some other miscellaneous uses of electromagnetic IH would include lost core melt out systems, de-bonding coatings from oil tanks and ship hulls, preheating rubber bushing for automotive air suspension, crystal growing, induction pumping of liquid metal, levitation heating, nanoparticle heating in hyperthermia, solar powered stirling engine test applications, optical fiber draw processing, induction thermal plasmas, processing of wastes, and many others.

2.4 Induction Melting
In the production of metal, it is necessary to raise the temperature of the metal or ore to the melting point and often to hold it at a temperature to allow certain metallurgical treatment. Electric furnaces used in metal melting are induction, arc, or resistance furnaces. The typical induction melting furnaces in use are the channel type and the crucible type that allow melting irons, steels, aluminum, copper, zinc, nickel, and other metals and alloys.

2.4.1 Induction Channel-Type Melting Furnace
The channel type induction melting furnace derives its name from its construction having a channel of molten metal passing through the magnetic core, which has a primary winding wound around it. The channel of molten metal acts like the secondary winding of a short-circuited transformer causing eddy current to flow through the metal being heated by the Joule effect. The channel is usually located at the bottom of the molten metal bath.
Channel furnaces are primarily suitable for continuous use and may often be fed by other types of furnaces. Channel furnaces are particularly advantageous for melting metals in such cases when

- High metal volumes are desired
- A certain product is produced
- Power outages are not expected
- Temperature uniformity is not critical

2.4.2 Induction Crucible-Type (Coreless) Furnace
The crucible type, or coreless induction furnace, consists of a solenoidal coil surrounding a crucible. Depending on the application, the crucible can be made from an electrically
conductive material (e.g., steel, graphite, etc.) or a non–electrically conductive material (e.g., ceramics, etc.). Electrically conductive crucibles are heated as a result of eddy currents induced from the inductor, increasing coil electrical efficiency when melting low resistive materials (e.g., aluminum, copper, bronze, magnesium, and some precious metals). The process of melting takes place thanks to thermal conduction from the heated crucible to the metal required to melt. Refractory liners are used for coil protection.

In the case of non–electrically conductive crucibles, the metal mass to be melted is located inside the pot formed by the refractory material. The refractory material may differ depending on the type of material and the required temperatures. This type of furnace requires no magnetic core as was in case of the channel-type furnace. External magnetic shunts may be used to control the external magnetic field exposure. The mixing or stirring action experienced in a coreless furnace is directly proportional to the power and inversely proportional to the square root of the applied frequency. A coreless furnace is a particularly good approach for melting metals in such cases when

- Precise temperature control is required
- Dross generation is high
- Lower capital and installation costs are desired
- Pre-melt capability is needed
- Power interruptions are expected

Coreless furnaces can be emptied very quickly to handle alloy changes on short notice. This provides maximum alloy flexibility, reducing job turnaround time and decreasing nonproductive and off-shift holding time.

### 2.4.3 Induction Vacuum Melting

The melting process can be carried out in a vacuum in order to eliminate concerns about oxidation and metal purity during the melting and casting processes. Because of the need to place the entire melting and casting system into one enclosure and to allow for any additions to the metal during the melt, this method can be quite costly and is reserved for use where the required purity of the product justifies the additional expense, such as the aerospace industry and military applications. Special methods of pouring the liquid metal are sometimes required when controlled amounts must be delivered to the mold at the time of casting.

### 2.5 Induction Welding

One of the major applications of electromagnetic IH is in the pipe- and tube-making industry. This includes the heating of a sheet of metal that has been formed into a tubular shape and constrained in such a way that eddy currents in the workpiece cause the two open ends of the sheet to be welded together producing the seam.

In order to do so, a cylindrical coil surrounds the tube’s V-shaped open seam area. Squeeze rolls press the strip edges together in the area where there is a maximum density
of the induced current providing a so-called forge weld. Typically, a water-cooled magnetic flux concentrator (magnetic impeder) is placed inside the tube, allowing it to increase the efficiency of the process.

Induction welding typically uses relatively high frequencies in the range of 200 to 600 kHz and power from 50 to 1500 kW [41]. Induction welding is usually a continuous operation. After welding, the seams are then subsequently annealed with a seam annealing system that follows the welding system in a continuous line.

2.6 Conclusion

As mentioned above, the industrial applications of IH can be divided into five large groups: heat treating, mass heating, special heating applications, induction melting, and induction welding. Because of space limitation, only the first three groups are discussed in this handbook. Induction melting and induction welding are outside the scope of this text. Although the basic thermal and electromagnetic phenomena are common for all induction applications, there are some distinguishing features in induction melting and induction welding that deal with technological uniqueness and process subtleties.

If the reader has questions or is interested in certain aspects related to the induction melting or induction welding processes, the authors suggest contacting the world-leading manufacturers of this equipment such as Inductotherm Corp. www.inductotherm.com, Consarc Corp. www.consarc.com, and Thermatool Corp. www.thermatool.com [41–43].