6

Induction Mass Heating

This chapter is devoted to a discussion of the use of induction heating (IH) for a large group of applications where metallic workpieces are heated before forging, forming, extrusion, bending, coating, drying, and the like. Typically, in such applications, it is required to through heat the entire cross section of the workpiece uniformly, that is why they are referred to as mass heating. However, in other cases, it is necessary to heat selected areas of the workpiece, developing desirable temperature gradients. Space does not permit discussing all possible mass heating applications. Therefore, this chapter focuses on the most typical ones.

6.1 Applications, Design Approaches, and Fundamental Principles of Induction Mass Heating before Metal Hot and Warm Working

The basic principles of IH of metallic materials for hot and warm working including heating dynamics, variation of coil electrical parameters, and redistribution of the heat sources during the heat cycle are similar to heat-treating applications discussed in Chapters 3 and 4. At the same time, there are some subtleties related, for example, to materials grades, target temperatures, workpiece sizes/shapes, and process requirements.

Steel components by far represent the majority of hot worked parts (Figure 2.20). At the same time, aluminum, copper, brass, bronze, cobalt, magnesium, nickel, and titanium as well as many other metals and alloys are also inductively heated for a number of commercial applications [1,30,473,476,479–481,486,489,535,539–542].

Temperature greatly affects the formability of metals and their ability to obtain desirable forms. Heating of a workpiece through its entire cross section to temperatures of the plastic deformation range creates a favorable condition for metal to be subsequently forced by various means into a desired shape. The most popular metal hot working processes for which induction mass heating is applied are as follows:

Forging: Billets, rods, bars, and the like are heated fully or partially, either in cut lengths or continuously, and are forged in presses, hammers (repeated blows), or upsetters (which gather and form the metal).

Forming: Hot and warm forming includes a variety of metal-working operations generally encompassing bending, expanding, spinning, and several others. The versatility of IH is associated with its ability to heat the workpiece entirely or its specific areas uniformly or certain regions can be intentionally heated to different temperatures creating desirable thermal profiles.
**Extrusion:** This process relies on forcing or squeezing heated materials through a die. Both ferrous and nonferrous metals and alloys are heated by electromagnetic induction before direct or indirect extrusions.

**Rolling:** Bars, billets, rods, slabs, blooms, strips, rings, and plates are rolled into the desired sizes and shapes.

In addition to obtaining desirable shapes, metallic components produced by warm and hot working often have enhanced structural integrity, superior mechanical properties, and better grain structure (e.g., having a more homogeneous structure, with reduced segregation and improved toughness, ductility, and fatigue) compared to cast materials. Fibrous grain structures developed after forging can be very beneficial. For example, if grain flow is oriented perpendicular to the most likely direction of crack propagation during service, then such structures can impede crack development and growth, improving impact and fatigue properties \[476,482–484\]. These and other factors make hot and warm metalworking attractive \[474,539–542\].

There is a wide range of workpiece sizes that are induction heated. For example, billet diameters can range from \(\frac{1}{2}\) in. (12.7 mm) to 8 in. (210 mm) and even greater. Some components are made from ingots or continuous cast metals and their alloys; others use wrought or powder metallurgy materials. Though specific applications may call for achieving certain desirable thermal gradients, in the great majority of IH, it is necessary to provide the metallic workpiece at a target temperature with the desired heat uniformity across its diameter/thickness as well as along its length and across its width/circumference.

### 6.1.1 Hot and Warm Working Steels

At hot forging temperatures (typically in the 1100°C to 1300°C or 2000°F to 2375°F range) and warm forging temperatures (815°C to 980°C or 1500°F to 1800°F), the microstructure of carbon steels is completely austenitic or predominately austenitic (depending on the steel grade).

Steel products (e.g., ingots, slags, billets, slabs, blooms, bars, etc.) are available in cast or wrought condition. Wrought steels originate from cast products but have gone through reheating (single or multiple) and plastic deformation. Wrought steels are typically more ductile, homogeneous, and structurally sound than cast steels and can take much greater thermal gradients during IH.

The optimal hot working temperatures are related to solidus temperatures. Because of a number of factors reviewed in Section 4.1, different batches of steel of the same grade do not have identical chemical composition. Table 6.1 shows allowable standard deviations in the composition of selected commercial steel grades according to SAE standards \[157\].

As can be seen in Table 6.1, it is not unusual for carbon steels to have a carbon content variation in the range of approximately 0.05% and even greater. Variation in carbon content alone can produce a more than 70°C (125°F) deviation in the solidus temperature \[187,188\]. Therefore, the optimal hot working temperature within a single steel grade can also vary depending on its exact chemical composition.

Steelmaking operations have improved over the years, and the steels obtained from a reputable supplier will often have relatively consistent composition with reduced (but not eliminated) carbon content deviation. Increased demand for obtaining a higher quality of shaped products in combination with always-present real-life deviations in the chemistry of given steel grade requires much tighter temperature control compared to tolerances that used to be acceptable a decade ago.
It is important to have a clear understanding of the potential impact of the variation of steel chemistries on processing practice and ways to adjust IH process recipe in order to ensure the best thermal conditions for a subsequent shaping operation. For example, steels with an excessive amount of sulfur are more difficult to forge. Also, steels with an excessive amount of low-melting temperature residuals could have a greater tendency for crack development during metal shaping. Selection of heating temperatures for warm and hot working is discussed in Section 6.1.4.

There is a large family of steels that are very close to plain carbon steels (based on their chemical composition), yet they form a separate steel category called microalloyed steels or high-strength low-alloy (HSLA) steels. It should be pointed out that HSLA steels are not considered alloy steels. Microalloyed steels include many standard and proprietary grades and are used in major steel market sectors. HSLA steels were developed to enhance certain properties of plain carbon steels, reduce production cost, and eliminate intermediate operations. Microalloying additions of V, Nb, Ti, Cr, Zr, Cu, Ni, and some other elements are used in various combinations. Typical examples of microalloyed steels are ASTM A242, A572, A607, A618, and A656. The amount of microalloying additions is at least an order of magnitude smaller compared to alloy steels. Regardless of a seemingly low amount of microalloying, the improvement in engineering properties could be substantial. The effects of different microalloying elements on the properties of steel products are discussed in numerous publications, including Refs. [30,50,160,228,233–235,477,533–537].

Microalloying additions have been utilized in low- and medium-carbon steels to improve industrial properties. Microalloyed forging steels can be economically advantageous as compared to traditional Q&T grades for a variety of forged components by reducing alloying additions (such as Cr, Ni, and Mo) and eliminating some post-forging processing operations (in particular, eliminating multiple steps of heat treatment) [30,188,535].

Ref. [160] suggests dividing HSLA steels into six categories based on their application and performance specifics:

- Weathering steels with enhanced atmospheric corrosion resistance utilizing small amounts of Cu and P.
- Microalloyed ferrite–pearlite steels with microadditions of carbide formers or carbonitride formers producing precipitation strengthening and grain refinement. Vanadium, niobium, and titanium are the three most frequently used microalloying elements in this subcategory for hot forging and rolling. The temperature range for forging niobium microalloyed steels is tighter than that for

<table>
<thead>
<tr>
<th>AISI-SAE Designation</th>
<th>Composition, wt.%</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>1010</td>
<td>0.08–0.13</td>
</tr>
<tr>
<td>1020</td>
<td>0.18–0.23</td>
</tr>
<tr>
<td>1040</td>
<td>0.37–0.44</td>
</tr>
<tr>
<td>1055</td>
<td>0.50–0.60</td>
</tr>
<tr>
<td>1080</td>
<td>0.75–0.88</td>
</tr>
<tr>
<td>1095</td>
<td>0.90–1.03</td>
</tr>
</tbody>
</table>

the vanadium steels. In both cases, control of the cooling rate after hot working is critical to ensure desirable engineering properties. Microalloying with V is an effective way to strengthen medium- and, in particular, high-carbon steels. These steels are noticeably more forgiving in providing acceptable properties over the wider range of processing temperatures compared to Ni microalloying. This feature alone might be an important factor when hot forging or rolling of large-size components and developing heating requirements.

• As-rolled pearlitic steels.
• Acicular ferrite steels with improved weldability and formability. Typically, the carbon content of these steels is less than 0.05% C.
• Dual-phase steels with an attractive combination of high ductility and high tensile strength thanks to the presence of martensite within a ferritic matrix.
• Inclusion-shape-controlled steels with improved through-thickness toughness and ductility and many others.

Although electromagnetic induction can be used for heating all the above-discussed steels before their subsequent processing and controlled cooling, it is most widely used at this point for the heating of as-rolled pearlitic steels and microalloyed ferritic–pearlitic steels.

Microalloying additions in ferritic–pearlitic steels modify engineering properties predominantly through the precipitation of carbonitrides during thermal or thermomechanical processing, increasing the strength (i.e., dispersive strengthening) and improving toughness (through microstructural refinement). Vanadium carbonitrides form at lowest temperatures, whereas titanium carbonitrides form at the highest temperatures. In contrast to niobium and vanadium, titanium nitrides do not dissolve at temperatures suitable for the majority of hot working applications including forging. Therefore, titanium does not provide strengthening precipitates during cooling, but fine TiN particles limit grain growth at forging temperatures [30].

It is important to be aware that although these microalloyed steels can exhibit hardness and fatigue properties comparable to Q&T grades, they sometimes exhibit lower impact strengths than Q&T forgings [30,188,535].

Though mechanical properties of microalloyed steels can be noticeably different compared to plain carbon and low-alloy steels, their electromagnetic–thermal physical properties do not typically exhibit dramatic differences.

6.1.2 Stainless Steels and Superalloys

Though plain carbon steels, low-alloy steels, and HSLA represent the largest markets for using IH in mass heating applications, there are a variety of other metals and alloys that routinely use electromagnetic induction to be heated.

6.1.2.1 Stainless Steels

Chromium (at least 11% Cr) is a principal alloying element in any stainless steel. Thin, semi-transparent, and dense chromium-rich oxide Cr₂O₃ film formed at the surface of the stainless steel billet or bar acts as a protective barrier that prevents the base material to further react with the gaseous or aqueous environment (e.g., salty atmosphere or environment containing dilute nitric acid). This protective mechanism is known as a process of passivation, and it is atmosphere specific and has been explained in many references including Ref. [236].

With increased chromium content, the corrosion rate can be reduced dramatically in a salty atmosphere or an environment containing dilute nitric acid; however, an increase in % Cr could cause an increase of the corrosion rate in dilute sulfuric acid.

Selected aspects related to stainless steels have already been discussed in Section 4.1.10. This section focuses on the specifics of IH stainless steels in mass heating applications.

Specifics of IH of stainless steels compared to heating plain carbon and low-alloy steels are related to differences in physical properties. Figures 3.3, 3.48, and 3.49 show a comparison of basic electrical and thermal properties of austenitic stainless steel SAE 304 versus medium-carbon steel. As a general trend, for temperatures below approximately 800°C, electrical resistivities $\rho$ of stainless steels are typically noticeably greater than those for plain carbon and low-alloy steels. At room temperature, the value of $\rho$ for stainless steel can be three to four times greater than that for plain carbon steel. For higher temperatures, this difference is not as dramatic and at the temperatures suitable for steel hot working, the difference is usually within the 20% range.

Since the austenitic subgroup of stainless steels are the oldest and most widely used in industry and taking into consideration that they are nonmagnetic, sometimes the term stainless is falsely associated with all grades of stainless steel by incorrectly assuming that all of them are nonmagnetic. There are several other grades of stainless steels that do exhibit ferromagnetic properties. However, magnetic stainless steels do not exhibit as strong ferromagnetic properties compared to plain carbon steel. On average, $\mu_r$ of magnetic stainless steels is at least three to five times lower than most plain carbon steels. Martensitic and ferritic categories of stainless steels exhibit the highest magnetic properties compared to other stainless steels. Besides, having lower $\mu_r$, magnetic saturation of stainless steels is also noticeably lower compared to plain carbon steels.

Both factors—greater $\rho$ and smaller $\mu_r$ of stainless steels—complement each other, resulting in greater current penetration depth $\delta$ compared to carbon steels. This leads to a deeper heating effect, particularly during the initial stage of heating.

Besides electromagnetic properties, there is a noticeable difference in the thermal properties of stainless steels versus carbon steels. Figure 3.48 shows that stainless steels have markedly lower thermal conductivities compared to carbon steels. This might be considered a noticeable disadvantage in achieving the heat uniformity because it manifests itself in reduced heat transfer via thermal conduction.

It is imperative to remember that there is a deviation of electromagnetic and thermal properties for different stainless steel categories and grades.

The specifics of electromagnetic and thermal properties of stainless steels have a counteracting effect on the ability to sufficiently heat the workpiece’s core. In some cases, it might be easier to heat the core of the workpiece because of the greater value of $\delta$ compared to heating of carbon steels, but in other cases, it might be just the opposite because of a lack of the “surface-to-core” heat flow owing to lower thermal conductivity. Numerical computer modeling helps determine the required modifications in heating recipes when IH a particular grade of stainless steel.
6.1.2.2 Superalloys

Superalloys (Ni–base, Fe–Ni–base, Co–base alloys, and some others) represent another large group of complex alloys that are often hot worked [520–523] and IH can be used for their preheating to a temperature range suitable for plastic deformation. There are a number of processes that can be used to produce superalloy components, including die forging, ring rolling, upsetting, extrusion, hot forming, and others. Ni-based alloys represent one of the oldest and the most widely used subgroup of superalloys that were developed to provide high strength (including creep-rupture strength) and low oxidation at elevated temperatures as well as high corrosion resistance. Superalloys are used in numerous industries including aerospace, medical, and petrochemical, just to name a few.

Superalloys often contain appreciable amounts of second-phase particles, different carbides, and intermetallic compounds. For example, Ni-based superalloys, besides having a nickel-based matrix (52%–78% Ni), may contain other major alloying elements including Cr (15%–20%), Mo (up to 18%), and Fe (3%–20%). Smaller amounts of W, Co, Ti, and other elements might be added to develop specific properties. The majority of superalloys are considered in engineering practice to be nonmagnetic materials (similar to austenitic stainless steels).

Because of superior ductility and structural homogeneity, many superalloys are used in a wrought form. However, some superalloys can only be fabricated and used in cast form [523].

Our experience shows that sometimes customers in their request for quotation (RFQ) do not provide detailed information regarding alloy grades to be processed; instead, they simply specify the IH of Inconel billets, for example. As one might expect, even the sub-group of Inconels alone represents a large family of special nonmagnetic alloys that have a common name/trademark—“Inconel”—but appreciably different properties. Therefore, when a customer requests heating Inconels or superalloys in general, it is actually very similar to when somebody asks about heating steels, aluminum, or copper alloys (i.e., compare physical properties of pure copper vs. brass or bronze). The same holds true for superalloys with common brand names or trademarks. To illustrate this statement, Table 6.2 shows melting points of selected superalloys versus stainless steel SAE 304.

The melting point of an alloy affects the maximum permissible temperature that can be reached during heating for plastic deformation. In turn, the maximum allowable temperature affects the thermal soaking condition and time required to achieve desirable surface-to-core temperature uniformity. It is widely accepted that the maximum permissible temperature should be at least 80°C–120°C lower than the melting point; otherwise, there is a concern for obtaining undesirable microstructures and irreversible damage to the alloy structure.

Electrothermal properties of different superalloy grades can have measurable variations that correspondingly affect the dynamics of IH, process protocol, and coil electrical parameters. As an example, Table 6.3 provides a comparison of electrothermal properties of two common Inconel grades versus stainless steel SAE 304.

Figure 6.1 [50,71,521,531] shows a comparison of electrical resistivity (Figure 6.1a) and thermal conductivity (Figure 6.1b) as a function of temperature for three selected Ni-based superalloy grades (In-600, In-625, and In-718) versus stainless steel (SAE 304).

Depending on application specifics, superalloys are usually heated to 950°C–1200°C (1750°F–2200°F) for forging and 1000°C–1230°C (1830°F–2250°F) in the case of extrusion. Some applications demand fine-grain microstructure of components made from superalloys. This translates into tighter temperature control when heating superalloys compared to plain carbon steels or stainless steels to ensure the proper deformation characteristics, minimum grain growth, and desirable structure. A requirement to suppress the grain coarsening does not permit using too high temperatures.
### TABLE 6.2
Comparison of Melting Temperatures and Densities of Selected Superalloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Melting Range °C</th>
<th>Density g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nickel Base (Wrought)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inconel 600</td>
<td>1355–1415</td>
<td>8.41</td>
</tr>
<tr>
<td>Inconel 617</td>
<td>1330–1370</td>
<td>8.36</td>
</tr>
<tr>
<td>Inconel 625</td>
<td>1290–1350</td>
<td>8.44</td>
</tr>
<tr>
<td>Inconel 690</td>
<td>1343–1377</td>
<td>8.14</td>
</tr>
<tr>
<td>Inconel 706</td>
<td>1335–1370</td>
<td>8.08</td>
</tr>
<tr>
<td>Inconel 718</td>
<td>1260–1336</td>
<td>8.22</td>
</tr>
<tr>
<td>Hastelloy S</td>
<td>1335–1380</td>
<td>8.76</td>
</tr>
<tr>
<td>Nimonic 942</td>
<td>1240–1300</td>
<td>8.19</td>
</tr>
<tr>
<td>Haynes 230</td>
<td>1300–1370</td>
<td>8.8</td>
</tr>
<tr>
<td>Rene 41</td>
<td>1315–1370</td>
<td>8.25</td>
</tr>
<tr>
<td>Udimet 500</td>
<td>1300–1395</td>
<td>8.02</td>
</tr>
<tr>
<td>Waspaloy</td>
<td>1330–1355</td>
<td>8.19</td>
</tr>
<tr>
<td><strong>Nickel Base (Cast)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IN-100</td>
<td>1265–1335</td>
<td>7.75</td>
</tr>
<tr>
<td>IN-738</td>
<td>1230–1315</td>
<td>8.11</td>
</tr>
<tr>
<td>IN-713C</td>
<td>1260–1290</td>
<td>7.91</td>
</tr>
<tr>
<td>Cast alloy 718</td>
<td>1205–1345</td>
<td>8.22</td>
</tr>
<tr>
<td>Nimocast 90</td>
<td>1310–1380</td>
<td>8.18</td>
</tr>
<tr>
<td>Udimet 500</td>
<td>1300–1395</td>
<td>8.02</td>
</tr>
<tr>
<td><strong>Cobalt Base (Wrought)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haynes</td>
<td>1300–1330</td>
<td>8.98</td>
</tr>
<tr>
<td>MP35N</td>
<td>1315–1425</td>
<td>8.41</td>
</tr>
<tr>
<td>L-605</td>
<td>1330–1330</td>
<td>9.13</td>
</tr>
<tr>
<td>Eligiloy</td>
<td>1495</td>
<td>8.3</td>
</tr>
<tr>
<td><strong>Cobalt Base (Cast)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haynes 1002</td>
<td>1305–1420</td>
<td>8.75</td>
</tr>
<tr>
<td>WI-52</td>
<td>1300–1355</td>
<td>8.88</td>
</tr>
<tr>
<td>MARM-M-302</td>
<td>1315–1370</td>
<td>9.21</td>
</tr>
<tr>
<td>MARM-M-322</td>
<td>1315–1360</td>
<td>8.91</td>
</tr>
<tr>
<td><strong>Iron–Nickel Base (Wrought)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incoloy 800</td>
<td>1355–1385</td>
<td>7.95</td>
</tr>
<tr>
<td>Incoloy 802</td>
<td>1345–1370</td>
<td>7.83</td>
</tr>
<tr>
<td>Incoloy 909</td>
<td>1395–1430</td>
<td>8.3</td>
</tr>
<tr>
<td>A-286</td>
<td>1370–1400</td>
<td>7.91</td>
</tr>
<tr>
<td>Discaloy</td>
<td>1380–1465</td>
<td>7.97</td>
</tr>
<tr>
<td>N-155</td>
<td>1275–1355</td>
<td>8.19</td>
</tr>
</tbody>
</table>


*Note:* Melting range of stainless steel SAE 304 is 1400–1450°C; density = 8.0 g/cm³.
One of the particularities of heating superalloys compared to austenitic stainless steels is related to higher electrical resistivity $\rho$ and lower thermal conductivity $k$. Forgeability and grain size of Ni-based superalloys and their final properties are more sensitive to seemingly minor variations in chemical composition compared to most stainless steels and carbon steels. This factor might require adjusting the heating recipe and target temperature for different lots and for forging different shapes made from the same material. Because of lower ductility and notch brittleness, some cobalt-based superalloys must be heated slowly and have sufficient time for surface-to-core heat equalization. Overheating may occur when superalloys are heated to the same final temperatures as stainless steels.
**Induction Mass Heating**

**Case Study.** Let us assume that, according to an RFQ, it is necessary to preheat a number of nonmagnetic alloys (including Inconels and stainless steel 304) before extrusion from room temperature to a maximum average (mean) temperature of 1200°C. It is reasonable to assume that the maximum allowable surface temperature might be specified to be 40°C greater than the average (approximately 1240°C). Since the melting point of stainless steel 304 is approximately 1400°C–1450°C, it most likely would be acceptable. However, for some superalloys (see Table 6.3), this maximum temperature is too close to the melting range with real potential for creating metallurgical problems related to overheating while trying to reach the required final average temperature.

Billets made from Inconel-625, for example, require longer heat times compared to stainless steel 304 because of lower thermal conductivity at all temperatures, producing a reduced surface-to-core heat flow. On the other hand, a reduction of $k$ will be compensated to some degree (but not completely) by higher values of $\rho$ and $\delta$.

### 6.1.3 Steel Surface Oxidation and Scaling

There is a tremendous amount of publications devoted to oxidation of steels and scale formation subtleties with respect to particular steel grades [4,28–30,33,151,162,196,259,488–517]. There is no intention to provide a detailed discussion on this subject here. Only a brief review that focuses on subjects relevant to IH of common steel grades will be provided.

In the presence of oxygen or being exposed to products of combustion at elevated temperatures, the steel’s surface is oxidized, forming scale (Figure 6.2a). Its amount is frequently expressed as % scale of the workpiece’s weight, thickness in mm, or weight in g/m², and it is primarily related to processing temperatures, time at elevated temperatures, the composition of the surrounding gaseous environment, workpiece’s surface conditions, steel’s composition and its tendency to be oxidized, as well as porosity of formed oxide/scale layer.

Certain steels have a reduced propensity to scale formation. For example, steels alloyed with Cr, Ni, and Mo are known for suppressed scale formation tendency; other steels might exhibit an intense oxidation, producing a substantial amount of scale.

Scale formation is a major concern to the industry since it has a multidimensional negative impact on overall cost-effectiveness and product quality. Elimination of scale or its significant reduction is imperative to steel processing companies. Studies show that, in the US steel industry, the large steel billets, blooms, slabs, and ingots being heated in gas- and fuel-fired furnaces form approximately 1% to 3% scale [492].

**FIGURE 6.2**
In the presence of oxygen at elevated temperatures, the steel’s surface is oxidized, forming scale (a). Development of transverse and longitudinal cracks (b and c) may be a concern when heating high-carbon steels, cast irons, and steel castings as well as other materials that exhibit low toughness.
Scale detracts from a value-added product and is associated with at least five major undesirable factors:

1. Loss of metal.
2. Scale adhesion issues may negatively affect the product quality and life expectancy of operating machinery. In some cases, scale adheres to the workpiece surface, making its removal via descaling (e.g., blasting, air/water jet descaling, brushing and reverse bending for wires and ropes, etc.) difficult. Scale can also alter mechanical and metallurgical properties as well as the surface quality of the final product, affecting reject quantity. In other instances, abrasive scaling adheres to parts of the forming or handling machinery, worsening tool wear, causing high friction conditions, shortening the life of dies and rolls, and producing scale pit marks. Additional operations including descaling, grinding, machining, shot blasting, and pickling may be needed as a result of poor surface finish associated with scaling. Various oxides have different descaling characteristics that complicate their removal.
3. Waste of energy. This factor has a multidimensional impact itself, including the amount of energy used to produce the scale. Since scale can cause premature failures of the hot working equipment including mill rolls and forging dies, it is also associated with energy consumption because of the need for repair work. Scale-related failures of hot working equipment are also linked to prolonged stoppages of the processing machinery, including induction systems, leading to the waste of energy associated with a standby operation (holding stage) as well as with shutting an induction line down, scale cleanup and starting it up again.
4. Dimensional inaccuracies and excessive metal allowances are associated with a metal loss as a result of scaling.
5. Capital-extensive maintenance programs and necessity of frequent scale removal and disposal. Scale affects the working conditions of induction heaters. The life of refractory linings, skid rails, and copper turns is directly affected by a scale generation. For example, one of the most frequent causes of forging coil failure is related to loose scale particle and scale dust penetration through microcracks and porosities of refractory developing large cracks and eventually leading to arcing between coil turns. Scale accumulation causes production interruptions of not only heating equipment but also downstream operations, requiring time-consuming, intense, and costly maintenance programs, which are associated with unproductive downtime.

The driver for scale formation is a chemical reaction between iron (Fe) and oxidizing gases (e.g., $O_2$, $CO_2$ [carbon dioxide], etc.), their composition, ratio, and mixture, as well as the presence of moisture that is contained in the atmosphere surrounding the heated workpiece. Several oxidation reactions occur, including the following [498,499]:

\[
Fe + \frac{1}{2} O_2 = FeO \\
Fe + H_2O = FeO + H_2 \\
Fe + CO_2 = FeO + CO
\]  

(6.1)

The thermodynamics of the iron oxidation can be quite complex, involving different stages and forms of oxides. Wagner’s theory is often used to quantify an oxidation process.
It is commonly accepted to consider the process of iron oxidation as being associated with the following mechanisms:

1. The penetration of oxygen from the surrounding atmosphere
2. The reactions at the “gas-to-scale” interface
3. The diffusion-driven processes in the “scale-to-base material” interface

Refs. [30,33,486,488] suggest that the first two mechanisms result in linear scale growth (the amount of scale is directly proportional to the amount of time that the iron is at elevated temperature), but the third mechanism results in parabolic growth kinetics (i.e., the amount of scale varies with the square root of time at temperature).

The final oxide structure that is formed is based on a combination of sequential and simultaneous formation of a variety of oxides. Under certain conditions, a particular type of oxide might be the dominant component. The fraction of each oxide in the composite (multilayer) scale depends on the activation and formation rate of each phase. Although iron and steel oxidize even at room temperature, we will be focusing here on their oxidation at elevated temperatures.

The oxidation of iron above 700°C can be approximated by three oxide layers developing on the surface—hematite Fe$_2$O$_3$, magnetite Fe$_3$O$_4$, and wustite FeO, being the iron-richest compound [30,33,486,488]. The innermost layer of composite scale consists of wustite (it forms next to the base metal), while intermediate and outside layers comprise magnetite and hematite, respectively. As reported in Ref. [33], the relative thicknesses of oxide layers within the 700°C to 1200°C range can be approximated as the following:

\[ \text{FeO, 95%; Fe}_3\text{O}_4, 4%; \text{Fe}_2\text{O}_3, 1\% \]

As suggested in Refs. [492,503], there is the following sequence of scale formation: the first formed oxide is Fe$_2$O$_3$, followed by Fe$_3$O$_4$ and FeO. These three types of iron oxides have different iron content: wustite consists of 77.7% of Fe; magnetite, 72.4%; and hematite, 69.9%. The expected oxide phases formed at specific temperatures can be roughly estimated using the iron–oxygen constitutional diagram (Figure 6.3) [33]. It is important to remember though that the Fe–O diagram assumes an equilibrium condition, which, strictly speaking, is not the case in IH and deviations are expected.

Physical properties of iron oxides are noticeably different. This includes thermal conductivity, mechanical properties (e.g., hardness, porosity, density, etc.), and descaling characteristics. Fe$_2$O$_3$ is a very “tight” oxide in contrast to FeO, which is “flaky” in nature and easier to remove. The hardness of different oxides varies substantially as well. Wustite hardness is in the range of 250–350 HV, while the hardness of magnetite is 1.5–2 times greater, but the hardness of hematite is approximately 3- to 3.5-fold higher compared to wustite [33].

Industry has developed several approximate formulas for a rough estimation of the thickness of the oxide layers. Refs. [512,513] suggest that in the case of high-temperature oxidation and when it can be assumed that the oxidation rate depends on the diffusion of metal ions and oxygen ions through the oxide layer, the following expression for a parabolic law can be applied:

\[ y = \sqrt{A_1 \cdot t}, \]  

where \( y \) is the oxide thickness, \( t \) is time, and \( A_1 \) is a material-specific constant.
The same sources suggest that in the case of a porous oxide layer (e.g., the oxygen has relatively free access to the metal), formation of the oxide layer may be approximated using a linear law:

\[ y = A_2 t, \]  

(6.3)

where \( A_2 \) is another material-specific constant.

As expected, the chemical composition of the surrounding gaseous environment has a measurable impact on oxidation rate and scale formation. For example, the presence of CO and H\(_2\) helps decrease the rate of iron surface oxidation. Increasing the amount of free oxygen noticeably accelerates the oxidation process and affects scale composition compared to scale formed in air [492].

Oxidation of steel is more complex than that of pure iron because of the presence of different alloying elements and residuals that may interact simultaneously or sequentially in a complex way. Some of the factors responsible for this complexity are as follows [500]:

- Different mobilities of metal ions in the oxide phases.
- Variation of solubility and diffusivity of different elements and oxides.
- Specifics of an internal oxidation of base metal consisting of different elements.
- Formation of ternary and higher oxides. For example, in silicon-containing steels (e.g., spring steels), Si has been shown to react with the oxide to form a complex iron–silicon oxide called fayalite—\( \text{Fe}_2\text{SiO}_4 \). Fayalite could noticeably affect adhesion properties at hot working temperatures. It has been reported [495] that because of its relatively low melting point, it might be challenging to descale such oxides in Si-containing steels. The liquid phase of fayalite penetrates with ease into the steel and any previously formed oxides, complicating their removal [496,497].

**FIGURE 6.3**

Expected oxide phases formed at specific temperatures and can be roughly estimated using the iron–oxygen constitutional diagram. (Based on data published in L. Samuels, *Light Microscopy of Carbon Steels*, ASM International, Materials Park, OH, 1999.)
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Studies reveal that the steels with greater carbon content exhibit a reduced amount of scaling. Figure 6.4 shows a comparison of the oxidation rates for several steels [500,501].

Various alloying and residual elements have different influences on the dynamics of oxidation and the amount of buildup scale. The chemical composition of the surface layer of the steel and its diffusion ability is subject to change as well. Refs. [512,513] suggest dividing the alloying elements in steel into three groups based on their affinity to $O_2$ and is summarized in Table 6.4.

![Figure 6.4](image_url)

**TABLE 6.4**
Summary of an Effect of Selected Alloying Elements on Steel Oxidation Based on Their Affinity to $O_2$

<table>
<thead>
<tr>
<th>Group #</th>
<th>Features of Oxidation Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I</td>
<td>Elements (e.g., Ni, Co, etc.) whose oxygen affinity is less than the affinity of the wustite. After saturation of the base metal with $O_2$, the outer oxidation of Fe promotes the formation of FeO.</td>
</tr>
<tr>
<td>Group II</td>
<td>Elements with oxygen affinity surpassing the iron (e.g., Cr, Si, V, Al). After saturation of the base metal with oxygen, the internal oxidation occurs. Formation of internal oxides of elements present in steel develops a protective barrier restricting the diffusion of metal and oxygen ions through it and suppressing scale formation. For example, stainless steels have been designed to be more scale resistant than plain carbon and low-alloy steels. Significant amount of chromium that is present in any stainless steel (&gt;12% Cr) will oxidize preferentially, forming a protective layer of chromium oxide on the surface, which dramatically reduces further oxidation rate.</td>
</tr>
<tr>
<td>Group III</td>
<td>Elements (Mo, W) with oxygen affinity similar to wustite. No measurable inner oxidation happens.</td>
</tr>
</tbody>
</table>

There are several ways to suppress the scale formation for a given steel grade. This includes the following:

1. Reducing the final (target) temperature. However, in many cases, this option is not realistic, because the use of lower-than-desirable temperatures could have a negative and costly impact on the subsequent metal-working operations (e.g., rolling, forging, extrusion, etc.) as well as on the quality of the final product, cracking, and equipment life expectancy by accelerating the tool wear.

2. Shortening the time for the workpiece's surface to be exposed to high temperatures in oxidizing atmosphere. This is the main reason for the significant scale reduction associated with using IH, because the workpiece reaches required final thermal conditions significantly more rapidly compared to most alternative heating methods (e.g., fuel combustion flame heating). Thus, the workpiece's surface remains at high temperature for a significantly shorter time. This ability of electromagnetic induction to substantially shorten the heat time as a result of in-depth heat generation and developing high power densities results in measurable reduction of the amount of built-up scale. For example, when IH of steel billets in air from ambient to temperatures of 1230°C–1260°C (2250°F to 2300°F) with subsequent air cooling to room temperature, there will be only approximately 0.35% and 0.31% of metal loss for SAE 1040 and 4340 steels, respectively [499]. When heating in gas furnaces, those numbers are usually three to five times higher. The capability of Inductoforge Technology to allow an instant change of power distribution along the heating line for different production runs and thus minimizing the time a metal is exposed to high temperatures is essential for scale reduction.

3. Application of controlled atmospheres (including inert, nonoxidizing, or weakly oxidizing environment) [162,166,167,541]. The use of protective (e.g., inert atmospheres such as argon and helium) or reducing gaseous atmospheres (e.g., nitrogen, nitrogen blended with small amount of hydrogen, methane, propane, or methanol vapor [368]) is a powerful way to dramatically reduce or even eliminate (practically speaking) surface oxidation and scale formation. The use of an endothermic gas in heating systems is also an option to reduce scale generation in steels. Endothermic gas is a mixture of different gasses, and its composition may vary based on the component gases and their mixture from having chemically inert properties to chemically active owing to the addition of enrichment gas. Note that some processing atmospheres may cause safety hazard to personnel, and the potential issue of safety must be addressed. Therefore, whenever a combustible working atmosphere or any other processing atmosphere is used, it is important to make sure that respected guidance, codes, and standards are closely followed (for example, National Fire Protection Association [NFPA] Standard 86C: “Standard for Industrial Furnaces Using a Special Processing Atmosphere,” http://www.nfpa.org). Several “hidden” reactions may take place when using different gaseous atmospheres. Therefore, the precise monitoring of atmosphere conditions, workplace wellness, and safety programs should be given the highest priority. Please remember: safety first. Nitrogen and nitrogen-based gaseous mixtures are popular choices because of their availability, relatively low cost, and environmental friendliness compared to other atmospheres. Keep in mind that air consists of approximately 78% of Ni and approximately 21% of O₂. Elimination or dramatic reduction of oxygen in the surroundings is imperative to suppress oxidation and reduce scaling. Elimination of
CO₂ in Ni-based atmosphere has a twofold effect: elimination/reducing oxidation and decarburation. Ref. [499] reveals that heating in pure Ni atmosphere to the same temperatures as in the previously discussed study and followed by air cooling resulted in 0.18% and 0.21% of metal loss for SAE 1040 and 4340 steels, respectively. Heating in a gaseous mixture of Ni with 5% natural gas assuming the same thermal conditions of the heated workpiece resulted in 0.18% and 0.24% metal loss for SAE 1040 and 4340 steels, respectively. Heating in Ni with 5% hydrogen under identical conditions resulted on 0.32% metal loss for SAE 4340 steel. Therefore, in this particular case study, a conclusion can be summarized as follows: the use of nitrogen atmosphere alone performed better compared to alternative atmospheres. However, it should be pointed out here that in other cases of heating different metallic materials, hydrogen–nitrogen mixtures could provide better results, markedly minimizing or eliminating surface oxidation. Precautions should be taken when applying hydrogen, because of its flammability and explosiveness.

4. Utilization of high thermal stability antiscale coatings and lubricants that prevent or noticeably reduce oxidation and scaling faces some economic challenges in mass production. Besides, those materials must comply with a number of regulations including environmental friendliness, preventing the production of toxic fumes, good adhesion, and safety. There are several pretreatment coating materials on the market. One of them is Lubrodal Sr-300, a product of FUCHS LUBRITECH GmbH, which can be applied in-line on a billet surface. The amount of reduction of the scale generation is reported in www.fuchs-lubritech.com (2016). Regardless of the effectiveness of antiscale coatings, their widespread use faces some practical challenges in a high-production environment, particularly when dealing with sizable billets and ingots. Some lubricants may help minimize an oxidation. For example, glass coating that is commonly used as a lubricant in extrusion practices provides a chemical barrier preventing oxidation.

In contrast to fuel combustion flame furnaces, it is easier to incorporate the protective atmospheres into the design of IH systems and, in particular, into vertically arranged inductors. In such applications, an inductor is encapsulated completely or partially using a specially designed chamber that is reliably sealed. At the beginning of the heating cycle, oxidized gases (such as air) are purged out of an inductor and a protective/reducing gaseous mixture is introduced using inlets located at the bottom of the induction coil. In case of using lightweight inert gases (e.g., such as helium), the protective gas or gaseous mixture being lighter than air will occupy the coil-to-workpiece heating space, forcing air out of the encapsulated vertical inductor, creating a nonoxidizing or low-oxidizing environment inside the heating chamber.

Some atmosphere leaks might occur during unloading heated billets and loading cold billets into the heating position. Therefore, care should be taken to prevent oxidizing gases (e.g., O₂) from entering the chamber. In order to maintain the required concentration of protective atmosphere inside the heating space, supplying an additional amount of gas mixture into the chamber should compensate for those leaks.

Horizontal single-coil and multicoil induction heater arrangements can also incorporate a protective or reducing atmosphere, though some challenges and precautions should be taken since gases can easily escape from unsealed or poorly sealed areas of an induction heater. Appropriate designs and sealing techniques (e.g., specially designed gaskets) are needed to provide a sufficient atmosphere circulation within the enclosure, minimizing gas leaks.
With in-line multicoil systems, it is imperative to encapsulate not only inductors but also the space between coils. Oxidation begins rapidly on the billet’s clean surface when exposed to the air after discharge from a chamber with protective atmosphere. The billet’s transportation time after discharge from the inductor and before entering subsequent forming machinery should be minimized.

The effectiveness of using nonoxidizing atmospheres might be greatly diminished as a result of surface preexisting conditions, for example, if the workpiece surface was previously highly oxidized and scaled.

The presence of moisture and water leaks should be minimized since they promote scale formation. It was reported [499] that SAE 1040 steel billets had more scaling than SAE 4340 grade in the atmosphere contaminated by water-cooling leaks.

The use of nonoxidizing or weakly oxidizing atmospheres can be an effective way to eliminate or dramatically reduce oxidation for not only carbon steels but also various nonferrous materials. This includes bright annealing of stainless steels and copper alloys. In such applications, an atmosphere that surrounds the workpiece (e.g., wires, rods, tubing, etc.) contains argon, nitrogen, or a nitrogen–hydrogen gaseous mixture excluding the presence of oxygen or maintaining its extremely low levels and producing a bright surface. Some of these applications were discussed in Section 2.1.4. As an example, Figure 6.5 shows two induction systems used for annealing copper tubing. Protective atmospheres not only can eliminate or reduce surface oxidation during the heat cycle but also can be used as the cooling agent during the initial stage of the cooling/quenching cycle (as it is in case of bright annealing).

6.1.4 Target Temperatures. Factors Associated with Steel Overheating

Required target temperatures depend on the heated alloys and specifics of a particular hot working process. For example, for plain carbon and alloy steels, the selection of forging temperatures is based on the following main factors: (1) carbon content, (2) alloy composition and residuals, and (3) the temperature range for optimum hot working conditions (including forgeability, the lowest forging pressure, and the amount of reduction) [489]. Table 6.5 shows a list of commonly suggested temperatures for selected ferrous metals and alloys before hot working [1,2,158,489,519,543].
In an attempt to increase metal plasticity and life of dies, some forgers have a tendency to increase the forging temperatures above the suggested maximum levels. This could potentially lead to steel overheating. “Overheating” is a very generic term representing a number of undesirable metallurgical phenomena and has been discussed in numerous publications, including Refs. [30,149,150,158,259,489–491,535]. Some aspects related to steel overheating that are particularly critical for hot working applications are briefly reviewed here. Accidental melting the most extreme case of overheating and being absolutely unacceptable will be excluded from consideration.

The occurrence of overheating worsens all critical properties of steel, including its ductility, impact strength, tensile strength, and others. Metallurgical “burning” is the severest form of steel overheating that results in a permanent irreversible damage to the structure. It causes intergranular liquation (also called incipient melting or grain boundary liquation) of low-melting phases and impurities (see Section 4.1.9), degradation of grain boundaries, and internal oxidation [33,162,166,167,268,490].

Steel burning is accompanied by severe grain coarsening and can be relatively easily detected by microscopic examination, revealing weakened grain boundary networking. Coarse-grain structures inevitably result in a reduced total grain boundary area, an area where the impurities are usually distributed and thus increasing their density. In contrast, fine-grain structures are associated with greater total grain boundary area with reduced concentration of impurities that, in turn, improves steel ductility and toughness.

If burning occurs, steel properties cannot be restored by heat treating or subsequent mechanical working requiring scrapping the workpieces. Impact properties of severely overheated steels may be negatively affected to an even greater degree than tensile strength and ductility.

**TABLE 6.5**

<table>
<thead>
<tr>
<th>Alloy (SAE Designation)</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>1010, 1015</td>
<td>1315</td>
</tr>
<tr>
<td>1020, 1030</td>
<td>1290</td>
</tr>
<tr>
<td>1040, 1050</td>
<td>1260</td>
</tr>
<tr>
<td>1060</td>
<td>1180</td>
</tr>
<tr>
<td>1095</td>
<td>1175</td>
</tr>
<tr>
<td>4130</td>
<td>1205</td>
</tr>
<tr>
<td>4140</td>
<td>1230</td>
</tr>
<tr>
<td>4340</td>
<td>1285</td>
</tr>
<tr>
<td>5160</td>
<td>1204</td>
</tr>
<tr>
<td>8620</td>
<td>1232</td>
</tr>
</tbody>
</table>

When discussing overheating, it is also important to consider the deformational and frictional heat generation that occurs during the steel hot working. Steel overheating might not occur after billet heating but as a result of additional heat generated during hot working. That combined with excessive temperatures after heating might be sufficient to result in a component failure owing to intergranular cracking, tearing, or rapture.

Overheating and burning are largely related to the melting point of a particular steel grade, the presence of residuals, and the time it is exposed to high temperatures.

As discussed in Section 4.1, residual elements in limited amount can be found in any steel. This is particularly so, because of the increased use of electric arc furnaces that utilize the recycled scrap, which may be relatively rich in Cu or other residuals that exhibit low melting temperatures. Over the last several decades, the amount of copper residual has increased in some commercial steel grades. Copper as a residual element is not readily oxidized and removed from liquid steel in the steelmaking process using electric arc furnaces [30,158,188].

Since copper has a relatively low melting point (1085°C) and taking into consideration that the solubility of copper in iron oxide FeO is quite low, at temperatures above its melting point, where the oxidation rate of iron is increasingly high, there is a rejection of the Cu from the oxide into the base metal, creating an enrichment of copper at the FeO oxide interface and forming a copper-rich phase [30,187,188,514,518]. Since the Cu is liquid at high temperatures, it can penetrate along grain boundaries with ease, dramatically weakening the grain boundaries and making them vulnerable for grain boundary liquation. In the presence of tensile stress, the deteriorated grain boundaries can cause cracking, resulting in a defect that is known as hot shortness (also referred to as red shortness).

Hot shortness is often defined as brittleness in a metallic material at hot forging temperatures, manifesting itself in a dramatic reduction of hot ductility. This issue becomes even more pronounced if steel contains an excessive amount of other low-melting point elements and nonoxidizing elements, with an excessive amount of copper being the major concern. Silicon additions can reduce the amount of copper-enriched phase, thus reducing the probability of the hot shortness in copper-containing steels and decreasing cracking susceptibility [487]. The suppression of scaling can reduce local liquated Cu-rich regions in steel.

Phosphorus and sulfur markedly affect steel overheating because of their tendency to segregate to austenite grain boundaries and also contribute to the “hot shortness.” Some of these factors as well as several other microstructural phenomena associated with steel overheating have been reviewed in Sections 4.1.8 and 4.1.9.

It has been reported [158,490,491] that the method of manufacture (e.g., electro slag remelted vs. vacuum remelted steels) also has a pronounced effect on steel overheating.

The formation of oxides beneath the surface of the heated steel (an internal oxidation) and surface decarburization are other highly undesirable phenomena associated with reaching excessive temperatures. The severity and degree of both phenomena increase with accelerated rate when steel is heated in air or in any other oxygen-contained environment while being exposed to increasingly high temperatures for extended times. Since in great majority of cases, we cannot dictate what steel should be used by a customer, reduction of the maximum (peak) temperature is the major way to reduce extents of decarburization. Reduction of the time when steel is exposed to oxidizing temperature is the second critical factor, which helps reduce but not eliminate a decarb. The decarb layer can only be eliminated by applying a special atmosphere, but it might be costly since it requires a gas chamber.

Another factor that often overlooked is the workpiece’s transportation time from an induction heater to a consequent metal working operation. For example, in some cases, a
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transportation time can exceed 10–15 s reaching several minutes. Such a prolonged workpiece transportation in free air at surface temperature level often exceeding 950–1000°C might be sufficient to promote appreciable surface decarburization in steels being in excess of 15–30 µm. Therefore, even in the case of using a special atmosphere during heating (completely eliminating surface decarburization and oxidation), the presence of relatively lengthy hot workpiece transportation on free air may be sufficient to promote measurable surface decarburization and oxidation.

Severely scaled, decarburized, and internally oxidized steels can produce several well-known undesirable consequences. For example, those layers or their traces might be seen in the wrought products as bands of decarburized materials containing oxide particles, islands, or clusters and may be entrapped during hot working [33]. Other factors have been discussed in Section 4.1.6.

It is imperative to keep the hot working temperatures sufficiently low such that none of the workpiece areas reach the temperatures close to steel burning while maintaining the maximum temperature required, thus minimizing flow stress and forging pressure. This maximum hot working temperature with a safety factor to account for both potential differences in chemistry and variations in temperatures within the heated workpiece is referred to as the maximum permissible temperature.

Carbon content is the dominant factor when determining the recommended hot working temperatures for both plain carbon and low-alloy steels. Care should be taken with steels high in silicon because of a significantly lower solidus temperature. Commonly recommended forging temperatures are approximately 165°C (300°F) below the solidus temperature for plain carbon steels and an additional 30°C–55°C (50°F–100°F) lower for alloy steels [187,188,535]. Above these temperatures, steels are subject to possible damage as a result of overheating, burning, and so on.

As stated earlier, when designing an IH system, it is typically required not only to raise the workpiece’s mean (average) temperature to a specified level but also to provide a certain degree of heat uniformity. The uniformity requirements may include maximum tolerable thermal gradients: “surface to core,” “end to end,” and “side to side.” As an example, a steel billet that is heated with appreciable nonuniformity can cause problems with premature die wear on hammers and presses and may require excessive force to form the metal. Precise temperature control during IH and the ability to obtain the required thermal condition of the workpiece are imperative for preventing the above-discussed undesirable phenomena associated with reaching excessive temperatures.

At the same time, there are cases when obtaining certain temperature gradients within the workpiece is desirable. For example, when heating certain aluminum alloys before direct or continuous extrusion, “leading” thermal gradients along the billet’s length are often preferable.

Commonly specified temperatures for selected nonferrous metals including superalloys are shown in Tables 6.6 and 6.7 and can also be found in Refs. [28,29,72,74,158,521–530,555]. Because superalloys were developed to exhibit greater strength/stiffness at elevated temperatures, it is more challenging for them to undergo metal working (e.g., forging, stamping, upsetting, or extrusion). This is particularly true for precipitation hardening superalloys [523].

In most cases, the initial temperature of the workpiece before IH is the room temperature. In other cases, the initial temperature is elevated and nonuniform, for example, after billet’s piercing or because of the uneven cooling of the slab, transfer bar, plate, or bloom as it progresses from the caster. Surface layers, and particularly the end and edge areas, become much cooler than the internal regions.
**TABLE 6.7**
Commonly Suggested Forging Temperatures for Selected Wrought Superalloys

<table>
<thead>
<tr>
<th>Superalloy</th>
<th>Forging Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upset and Breakdown</td>
</tr>
<tr>
<td></td>
<td>°C  °F</td>
</tr>
<tr>
<td>Iron-Based Alloys</td>
<td></td>
</tr>
<tr>
<td>A-286</td>
<td>1095  2000</td>
</tr>
<tr>
<td>V-57</td>
<td>1095  2000</td>
</tr>
<tr>
<td>Cobalt-Based Alloys</td>
<td></td>
</tr>
<tr>
<td>J-1570</td>
<td>1175  2150</td>
</tr>
<tr>
<td>J-1650</td>
<td>1150  2100</td>
</tr>
<tr>
<td>S-816</td>
<td>1150  2100</td>
</tr>
<tr>
<td>Haynes 188</td>
<td>1205  2200</td>
</tr>
<tr>
<td>Nickel-Based Alloys</td>
<td></td>
</tr>
<tr>
<td>Astroloy</td>
<td>1120  2050</td>
</tr>
<tr>
<td>Hastelloy W</td>
<td>1205  2200</td>
</tr>
<tr>
<td>Inconel 600</td>
<td>1150  2100</td>
</tr>
<tr>
<td>Inconel 700</td>
<td>1120  2050</td>
</tr>
<tr>
<td>Inconel 718</td>
<td>1095  2000</td>
</tr>
<tr>
<td>Incoloy 901</td>
<td>1150  2100</td>
</tr>
<tr>
<td>Waspaloy</td>
<td>1160  2125</td>
</tr>
</tbody>
</table>

6.1.5 Design Concepts

Within this chapter, the term *billet* is used to represent a number of similar workpiece shapes, including solid/hollow billets, rods, bars, slugs, and so on.

In the past, fuel-fired furnaces that utilized natural gas, fuel oil, or liquid petroleum gases were often used because of the low cost of fuel. However, in recent decades, producers have shifted their preference toward IH systems, and this tendency continues to grow at an increasing pace. The main reasons responsible for that shift have been outlined in Chapter 2 as well as in other sections of this book and in Refs. [2,7–13,36,187,188,485].

Induction mass heating applications are typically more power demanding and time consuming than induction heat treating. The power ratings of IH machines range from less than 100 kW up to dozens of megawatts.

Round or square stock sizes from approximately 6 mm (1/4 in.) to greater than 0.2 m (8 in.) are commonly used. Occasionally, diameters of billets and bars can be up to 0.48 m (19 in.). Applied frequencies are typically from 50/60 Hz to greater than 70 kHz for smaller sizes.

A designer often faces the necessity to achieve a reasonable compromise among often-contradictory process requirements and design criteria when designing induction mass heating systems [2,36,544–547]. Cylindrical and rectangular solenoid multiturn induction coils are most often used in induction mass heating applications.

The four basic heating modes in induction mass heating (Figure 6.6) are as follows:

*Static heating*: In the static heating mode, the workpiece is placed into an induction coil (vertical or horizontal) for a given period while a set amount of power is applied until it reaches the desired thermal conditions (Figures 6.6a and 6.7a). Then, the workpiece is discharged from the induction heater and delivered to the metal-forming station. The next workpiece to be heated is loaded into the coil and the process is repeated.

![FIGURE 6.6](image_url)

Basic heating modes in induction mass heating. (a) Static heating. (b) Progressive multistage heating and continuous heating. (c) Oscillating heating.
Progressive multistage heating: This heating mode is used when two or more heated workpieces (e.g., billets) are moved (via a pusher, an indexing mechanism, a robot, a walking beam, or other means) through a single coil or multicoil induction heater. Therefore, the entire component or certain portions of it are sequentially heated (in a progressive manner) at certain predetermined heating stages inside the in-line horizontal inductor (being more typical) or a multipost vertical or horizontal heater (Figures 6.6b and 6.7b).

Continuous heating: With the continuous heating mode, the workpiece is moved in a continuous motion through one or more coils (Figures 6.6b and 6.7c). This heating mode is commonly used when it is required to heat long components such as bars, slabs, strips, wires, blooms, and rods.

Oscillating heating: A workpiece moves back and forth (oscillates, Figure 6.6c) during the process of heating inside a single-coil or multicoil horizontal induction heater with an oscillating stroke featuring a space-saving design approach.

When designing modern induction mass heating systems, temperature uniformity of the heated workpiece is only one of the goals. Additional design criteria include maximum production rate, minimum metal losses, and the ability to provide a flexible, energy-efficient, and compact system. Other important factors include quality assurance, process repeatability with piece-by-piece processing, robustness, automation capability, environmental friendliness, reliability, and maintainability of the equipment. The last criterion, but not the least, is the competitive cost of an IH system.

One of the challenges in IH arises from the necessity to provide the required surface-to-core temperature uniformity. Because of the physics of the process, the workpiece core tends to be heated noticeably slower than its surface (transverse flux inductors and traveling wave inductors are exceptions from the rule). The main reason for the heat deficit in the core of the heated component is the skin effect.

As discussed in Section 3.1.2, the skin effect depends on the electromagnetic properties and frequency. Because of this effect, 86% of the power is induced within the surface layer (“skin” layer), which is called the current penetration depth and can be calculated...
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according to Equations 3.6 and 3.7. Current penetration depths of nonmagnetic metals and carbon steels versus frequency and temperature are shown in Tables 3.4 and 3.5.

According to a classical definition of the skin effect, the induced current decreases from the surface toward the internal area of the heated body. When heating solid cylinders using solenoid-type inductors, regardless of applied frequency, there are no heat sources induced in its core. The core is only heated thanks to thermal conduction from the regions having higher temperatures (e.g., workpiece’s surface). The nature of the heat transfer phenomena and a description of its three modes (thermal conduction, heat convection, and thermal radiation) were discussed in Section 3.2.

In induction mass heating, the heat transfer by convection and radiation reflects the value of surface heat loss, which varies with temperature (Figure 3.50b). In hot working applications (including IH of steel, titanium, tungsten, and superalloys), radiation losses are much greater than convection losses, representing the major portion of total heat loss from the workpiece surface.

It is typically much easier to provide surface-to-core temperature uniformity for metals with high thermal conductivity such as aluminum, silver, magnesium, or copper. Metals with poor thermal conductivity, including stainless steel, titanium, some superalloys, carbon steel, and some other alloys, require extra care in order to obtain the desired temperature uniformity. This “extra care” includes proper selection of heat mode, frequency choice, process time, and other parameters.

Figure 6.8a shows the typical time–temperature curve for static IH of a nonmagnetic solid cylinder. Immediately after heating begins, the surface temperature and average temperature begin to rise. In contrast, there is a delay before the core temperature starts to grow. If the material properties are constant and surface heat losses are absent, there will be a linear region where all three temperatures (surface, average, and core) are represented by three straight lines (Figure 6.8a, solid lines). The surface-to-core temperature difference

![Figure 6.8](image-url)

**FIGURE 6.8**
Typical time–temperature curve for static IH of a nonmagnetic solid cylinder (a) and an application of pulse heating mode consisting of a series of “Heat ON” and “Heat OFF” cycles until the desired uniformity is obtained (b).
in this area is proportional to the power density during the heating cycle, the frequency, geometry, and material properties of the workpiece.

As soon as power is cut off, the surface temperature decays because of thermal conduction toward a cooler core. It is during this stage that is commonly referred as soaking as the surface-to-core differential decreases improving its radial temperature uniformity.

In reality, the surface-to-core temperature differential starts to decline during the heating stage (Figure 6.8a, dotted curve representing surface temperature). This takes place because of the rising surface heat loss with temperature as well as because of a current penetration depth increase with temperature (Figure 3.14).

The soaking stage can take place when the heated workpiece is inside the induction coil or during its transfer to the forming machinery.

Actually, the time–temperature profiles are more complex than those shown in Figure 6.8a owing to the nonlinear characteristics of physical properties (Figure 2.11). In order to improve the performance of an IH machine and reduce the heating time while providing the required surface-to-core temperature uniformity, power pulsing can be applied. Power pulsing refers to a technique that applies short bursts of power to maintain a desired surface temperature or a maximum allowable surface-to-core temperature difference. Pulse heating consists of a series of “Heat ON” and “Heat OFF” cycles until the desired uniformity is obtained (Figure 6.8b). Depending on the particular application specifics, the process time reduction with pulse heating compared to conventional heating can exceed 25%.

The heating time can be further reduced when applying accelerated heating (Figure 6.9a). According to this heating mode, the workpiece’s surface temperature is raised to a maximum permissible level as fast as possible, allowing thermal conduction to develop intense heat flow from the surface and subsurface regions toward its “colder” core. Then, a gradual reduction of the heating power is required to maintain the surface temperature.

Accelerated heating is typically used for heating small- and medium-sized workpieces that have sufficient toughness (i.e., SAE 1006, 1008, and 1010 steels). These steels can

![FIGURE 6.9](image-url)

Accelerated heating mode (a) and modified accelerated heating (b).
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normally withstand substantial thermal gradients (assuming wrought condition and the absence of considerable stress risers or severely heterogeneous microstructures).

The accelerated heating may have several modifications. Figure 6.9b shows one such modification that is particularly useful when heated workpieces exhibit brittleness. Transverse and longitudinal cracks (Figure 6.2b and c) may be a concern when heating iron castings, high-carbon steels, and other materials with low toughness. These cracks may appear because of excessive thermal stresses. The permissible magnitude of such thermal gradients is a complex function of geometry, chemical composition, prior processing conditions (e.g., as-cast or wrought steel), microstructural irregularities, and temperature.

As-cast steels and cast irons are particularly prone to cracking under intense heating and need special attention. Solidification defects (including shrinkage, macro- and microsegregation, and porosity), gas defects (e.g., blowholes/pin holes, intergranular porosity, entrapped air pockets, etc.), hot tears, presence of cavities, large inclusions, decarburized layers, intergranular oxidation, microcracks, and other stress risers have a pronounced effect on maximum permissible heat intensity and thermal gradients particularly during the initial heating stage, even when heating steels with low and moderate carbon content. For example, medium-carbon steels (e.g., SAE 4140 steel with approximately 0.4% C) under as-cast conditions should not be heated by applying classical accelerated heating if they have a substantial amount of as-cast imperfections in their microstructure. Modified acceleration heating (Figure 6.9b) should be used instead.

Though it has been mentioned above that the curves shown in Figures 6.8 and 6.9 illustrate typical time–temperature profiles that take place during static heating, these curves can represent progressive multistage heating and continuous heating. In the case of multistage or continuous heating, the time axis represents the length of the induction line. Bursts of power can represent the power of in-line coils that may have different lengths and windings and can be individually fed from different power supplies with the ability to adjust the output power or having series/parallel connection to a single inverter.

The selection of power, frequency, and coil length in induction mass heating applications is highly subjective, depending on the type of heated metal, required temperature uniformity, time of heating, and other factors.

Frequency is one of the most critical parameters. If the frequency is too low, eddy current cancellation could take place, resulting in poor coil electrical efficiency and, in some instances, in an inability to reach the desired temperature (see case study shown in Figure 4.71). However, a very high frequency results in a highly pronounced skin effect leading to eddy current concentration in a very fine surface layer compared to the diameter/thickness of the workpiece. In this case, a long heating time will be required to assure sufficient heating of internal areas and the core because of thermal conduction. A prolonged heat time results in an increase of the surface heat losses that, in turn, reduce the thermal efficiency of the induction heater and diminish the main advantage of IH—short heat time. Typically, an induction heater is designed to be able to heat a range of workpiece sizes. Therefore, frequency selection is often a reasonable compromise.

As a rule of thumb, when heating solid cylinders using conventional solenoid coils, current cancellation will not take place if the workpiece diameter-to-δ ratio is greater than four.

Selecting the length of an induction heater is another important step in specifying an IH system. In determining how long the coil line needs to be, the time needed for heating the workpiece to a required thermal condition is actually being determined. Heating time is a complex function of various factors including the size of the workpiece, frequency, heating mode, power density, maximum temperature that is allowed any time during the heat cycle, material properties, and the specified surface-to-core temperature uniformity.
Numerical computation is the most accurate technique to determine the coil length as well as other coil design parameters [550–554]. At the same time, over the years, an industry has developed several techniques for rough estimation of basic process parameters. The procedure for rough estimation of the required power was discussed in Section 3.3.

A ballpark number for determining the minimum heat time and coil length when heating carbon steel cylinders from room temperature to temperatures in the forging range can be obtained using the following empirical formulas:

\[
\text{Minimum heat time} = 25 \times D^2 \tag{6.4}
\]

\[
\text{Minimum coil length} = 0.03 \times (\text{lb/h}), \tag{6.5}
\]

where \(D\) is the diameter of the solid cylinder (in inches), time is measured in seconds, and coil length is measured in inches.

Coil design is of course an extremely important factor in developing an efficient IH system. Although there are several coil styles available and successfully used in different applications of mass heating, solenoid-type (helical) multiturn coils are the most frequently used. The basic requirements for selecting the coil style include the following:

- Safety principles (electrical, mechanical, etc.)
- An ability to do the heating job, providing the workpiece’s needed thermal conditions
- Mechanical and electrical integrity assuring long-lasting coil life
- Low cost of fabrication, operation, maintenance and repair, and so on

It is imperative that coil design should comply with standards and regulations, including those of the Occupational Safety & Health Administration (OSHA), the World Health Organization (WHO), the Institute of Electrical and Electronics Engineers (IEEE), and others. If required, magnetic shunts made of lamination packs can be effectively used to reduce external magnetic field exposure around an inductor and to protect electrically conductive devices positioned in its proximity (e.g., support rolls, enclosure, electronics, etc.). As an example, Figure 6.10 shows the results of numerical modeling, providing a comparison of electromagnetic field distribution of a bare coil (Figure 6.10a) versus a coil with U-shaped shunts (Figure 6.10b).

Coil-to-workpiece electromagnetic coupling have a marked effect on the coil’s ability to deliver heating power to the workpiece. Smaller gaps between the surface of the heated workpiece and the coil copper result in better electromagnetic coupling and, consequently, higher coil electrical efficiency. However, it is wise to remember that according to Equation 3.36, the total efficiency of the induction coil is a product of both electrical efficiency and thermal efficiency.

The great majority of induction coils for mass heating consist of thermal insulation (also called refractory or liners) positioned between the coil and the heated workpiece protecting the copper windings from heat exposure.

The thermal refractory dramatically reduces the heat losses from the surface of the heated workpiece. At the same time, the use of a refractory necessitates larger coil-to-workpiece gaps, which, in turn, reduces coil electrical efficiency (Figure 3.52a). Thus, on one hand, the presence of the refractory allows the improvement of coil thermal efficiency, but it also requires an additional space for its installation and negatively affects electromagnetic
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coupling. In the great majority of mass heating applications and, in particular, heating before hot working, it is typically advantageous to use a refractory. Refractory thickness usually varies from \( \frac{1}{4} \) in. (6 mm) to 1.5 in. (38 mm) depending on application specifics.

Different materials can be used for a refractory fabrication. These include castable (i.e., Visil), high-temperature cement, silicon carbide, alumina, H-91, Zircar, sialon, and other fibrous ceramic materials.

There are two basic approaches to building coils: the open-wound or the refractory-encased approach [2]. The open-wound method provides more convenient repair in the event of failure, but the choice is never that simple.

Replaceable refractory liners are commonly utilized in the construction of open-wound coils (Figure 6.11a). Coils with replaceable liners have lower repair time and cost compared to cast coils.

Although the encased coil using a castable refractory offers durability and longer life, it still follows recommended maintenance routines that should not be neglected. To repair

FIGURE 6.10
Results of computer modeling providing a comparison of electromagnetic field distribution of a bare coil (a) versus coil with U-shaped shunts (b).

FIGURE 6.11
Replaceable refractory liners are commonly utilized in the construction of open-wound coils (a). Support rails terminate beyond the open-wound coil box envelope (b).
a cast coil, it must be shipped to a service center where it is broken down to the bare coil. Then, the coil must be repaired, reinsulated, and recast. This process is time consuming considering that the operator can replace refractory liners on site in a matter of minutes for an open-wound coil.

Self-supporting internal skid rails or skid plates to protect the liner surfaces, either water-cooled or not water-cooled (depending on application specifications and temperature range), must be robust enough to carry the full load of processed workpieces, supporting their weight with minimal deflection and wear. At the same time, support rails should be transparent enough to the electromagnetic field such that they will not overheat or negatively affect the energy effectiveness of the process.

Water-cooled rails are positioned inside the coil where a strong magnetic field is present; thus, their presence is associated with some kilowatt losses owing to induced eddy currents. There is also an appreciable heat transfer from the heated workpieces toward the skid rails as a result of thermal conduction. Since skid rails are positioned along the entire coil length and terminate beyond the open-wound coil box envelope (Figure 6.11b), the additional expansion of longer rails during heating must be accommodated to prevent their bowing and bending.

Skid rails exhibit localized heat sink to an area of the heated billets in contact with rails. This could potentially produce localized cold spots that might also produce noticeable heat nonuniformity. Besides that, it can also lower the mean temperature of smaller-sized billets fabricated from high thermally conductive materials. Tubing may be provided with an extra heavy wall section that affords a much thicker wear area, reducing the pressure from the billets and minimizing the cold sink effect.

In order to extend the life of water-cooled skid rails, they are wear coated on the wearing side. Several proprietary techniques are used to fuse/weld/coat materials with good wear resistance properties to the surface of rails. Stellite is often applied to the surface of the rails as a wear-coating material. An oxygen acetylene torch or, in other cases, a less labor-intensive plasma coating process allow the application of a wide variety of materials including nickel-based hard-faced wear coating, tungsten carbides, and others.

Depending on the weight of workpieces needed to be supported by rails and operating frequency, water-cooled skid rails are fabricated from nonmagnetic stainless steels or Ni-based superalloy tubing having diameters within the 4- to 12-mm range (smaller diameters are chosen from higher frequencies and lighter weights). Care should be taken to avoid conditions where tubular skid rails are deformed because of the excessive weight of the heated billets, restricting cooling water flow and overheating that result in their premature failure.

As an alternative to water-cooled tubular skid rails, solid rods of small diameters may also be applied as skid rails in some low-temperature/low-power applications. Various ceramic materials and even tempered glasses (if maximum temperature permits) may also be applied as wear plates/skid rails when processing lightweight workpieces (e.g., small aluminum billets). However, care must be taken to avoid excessive impact loads because of the relative brittleness of such materials.

Most manufactured coil liners are round. For cylindrical billets, a round-shaped liner naturally suits the coil geometry. However, when heating square billets, this mismatch of shapes may result in a noticeable increase of the coil opening in addition to space allowances for the skid rails and thermal insulation. This affects not only heating efficiency but often the load-matching capability as well.

The coil turn space factor $K_{\text{space}}$ is another important parameter of the coil design and should be as high as possible. The $K_{\text{space}}$ indicates how tightly the coil turns are wound (see
Section 3.1.7.1). The space between turns should be as small as possible yet large enough to leave room for electrical insulation. The coil turn space factor for a multiturn coil is typically in the range of 0.7 to 0.85.

High-conductivity round, rectangular, and square copper tubing are commonly used for coil fabrication because it is naturally profiled for water cooling and because copper is a good electrical and thermal conductor with mechanical properties suited for coil fabrication. In some rare cases, copper tubing does not provide a large enough area for energy transfer. To compensate for tube water passage constraints, a copper strip is sometimes brazed to the external water-cooling copper tube. Coil cooling is a very important aspect of induction heater design and has already been discussed in Section 4.2.4.4.

There are two principal sources of the heat generation within the coil copper turns:

- Joule heating effect produced by the coil carrying electrical current
- Absorption of the heat from the workpiece

Therefore, means must be taken to avoid heat accumulation over time, keeping the copper temperature sufficiently cool during the entire heat cycle. Similar to heat-treating designs, in mass heating applications, this is accomplished by incorporating an appropriate number of water-cooling circuits. It is not unusual that a single coil might have several water-cooled circuits (Figure 4.72).

Square, rectangular, and round copper tubing are the most popular tubing used in the fabrication of solenoid coils for mass heating. Copper tube wall thickness is largely chosen based on the system operating frequency. For example, a system with a low operating frequency requires a thicker wall tube than a high-frequency system. This fact is directly related to the current penetration depth in the copper ($\delta_{Cu}$) and holds true for both coil copper tubing and coils made from copper sheet (Table 4.18). A coil tubing wall that is smaller than $1.6\delta_{Cu}$ reduces coil efficiency and increases copper tubing kilowatt losses.

In high-frequency applications, the tubing wall may be thicker than that calculated according to the abovementioned recommendation. This is because it may not be mechanically feasible or reliable to use very thin wall tubing owing to the mechanical flexing caused by electromagnetic forces (EMFs). As the frequency is lowered, more attention must be paid to coil support, as there is more vibration at lower frequencies, particularly experienced by the turns near both ends of multiturn solenoid coils [396,397].

Low-frequency applications are often an exception of this rule regarding the selection of the copper tubing wall thickness discussed above. For example, current penetration depth in copper at 60 Hz at ambient temperature is approximately 9 mm (3/8 in.). Therefore, the use of copper tubing with such a thick wall is often impractical, which leads to poor removal of the heat owing to thermal conductivity and making the construction bulky, heavy, and costly.

High-dielectric epoxies, nonelectrically conductive tapes, and some nyons are commonly used as dielectric insulating materials that eliminate arcing between coil windings. A fluidized bed process or electrostatic coating can provide dielectric insulation. In certain cases, some ceramic coatings provide both protection from high-temperature exposure and suitable dielectric strengths.

Though being the most popular, solenoid multiturn coils are not exclusively used in mass heating applications. Other inductor styles include channel inductors, oval coils, pancake and hairpin inductors, traveling wave, transverse flux, “C” core inductors, and some others. Different inductor styles will be reviewed in corresponding sections of this chapter.
6.2 In-Line IH of Long Cylinder Bars and Rods

6.2.1 Electrothermal Nature of In-Line IH

Modern techniques for producing long products of general cylindrical shape bars and rods integrate three stages of production: casting, reheating, and rolling into a continuous line.

Within this chapter, the term bar is used to represent a number of similar workpiece shapes, including solid/hollow bars, rods, slugs, long billets, and so on.

Depending on the process parameters, an induction bar heating system may consist of one or several in-line coils (Figure 6.12). One of the challenges with in-line IH arises from the fact that the surface-to-core temperature profile continues to change as the bar passes through the line of induction coils. At the same time, if there are appreciable axial gaps between sequentially processed bars, then the regions of their leading and trailing ends have a tendency to heat with greater intensity compared to the body of the bar (Figure 3.37).

Experience gained on previous jobs and the ability to provide accurate mathematical modeling of the process serve as a comfort factor when designing new in-line IH systems. As an example, Figure 3.53 shows the results of the transitional and final heating conditions of a 76-mm-diameter (3-in.-diameter) carbon steel bar and its surface-to-core temperature profile along the IH line comprising eight coils positioned in-line. Coil parameters were provided in Section 3.3.2.

Figure 3.54 shows surface-to-core temperature profiles and power density (heat source) distribution along the radius of the bar at different locations along the heating line after establishing steady-state thermal conditions (scales of power density profiles are different for various coil positions).

At the initial heating stage, the entire bar is ferromagnetic and the skin effect is pronounced. All power induced in the bar appears in the fine surface layer, which typically
Induction Mass Heating does not exceed 6 mm (0.25 in.) for frequencies 500 Hz and up. Because of the relatively low temperature at this stage, the surface heat losses (Figure 3.50b) are quite low. Both factors lead to a rapid increase in temperature at the surface with a minor change at the core. Intensive surface heating produces a significant surface-to-core temperature gradient.

During the initial heating stage (also called the magnetic stage), the coil efficiency is quite high (typically >80%) and continues to rise because of an increase in steel electrical resistivity with the temperature (Figure 3.3). Because the surface temperature is still below the Curie point during heating in Coil #1, the skin effect is very pronounced and magnetic permeability remains high, and a slight reduction of \( \mu \) does not affect the climb in electrical efficiency (Figure 3.54a). After a short time, the coil efficiency reaches its maximum value and the efficiency starts to decline.

The next stage is referred to as an interim stage. It takes place when the surface temperature exceeds the Curie point (i.e., after exiting Coil #3, Figure 3.54b) and the intensity of heating noticeably decreases (assuming constant current or voltage at coil terminals). This takes place as a result of a number of reasons including [21]:

- The surface of the carbon steel bar loses its magnetic properties, becoming non-magnetic and \( \mu \) drops to 1. As a result, the power density generated within the bar and coil electrical efficiency decline.
- The specific heat has its maximum value (a peak) near the Curie point (Figure 3.49b). The value of the specific heat denotes the amount of energy that must be absorbed by the metal to achieve the required temperature rise.
- Surface-to-core thermal gradient is increased, resulting in more intense heat flow toward the cold core.

At this stage, the electrical resistivity of the carbon steel increases approximately two or three times compared to its value in the initial stage (Figure 3.3). At the same time, the decrease in \( \mu \) is much more pronounced (40 times and even higher depending on the steel grade, prior microstructure, and coil power), as illustrated in Figure 3.8a. Both factors cause a 6- to 10-fold increase in \( \delta \) (Figure 3.14a). A significant portion of the power is now generated in the internal layers of the bar. Though the bar surface becomes nonmagnetic, the bar’s subsurface region retains its magnetic properties. The interim stage exists as long as the thickness of the nonmagnetic layer is less than the 2*\( \delta \) in the hot steel.

During this stage, the induced eddy current and power density distribution along the radius of the bar have a unique wave-shaped form. Figure 3.54b (left) reveals that after exiting Coil #3, the maximum power density is located at the surface. Then, it decreases toward the core. However, once it reaches a certain distance from the surface, the power density starts to increase again, owing to the remaining magnetic properties of the steel below the surface. The nature of this phenomenon has been discussed in Sections 3.3.2 and 4.2.2.4.

The final heating stage (nonmagnetic stage) takes place when the entire cross section of the bar becomes nonmagnetic and the power density will then resemble its classical exponential distribution (i.e., after exiting Coil #8, Figure 3.54c).

There are several circuits of coil-to-power supply connection available [36]. According to one of the conventional designs, a single power supply would power an entire coil line. The 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 parallel and series tuning. As an example, Figure 6.13a shows an in-line three-coil IH
system with coils connected electrically in series (left) or in parallel (right) and fed by a single inverter. The choice of coil connection is primarily affected by the type of power supply, its load-matching capability, and the necessity to avoid voltage or current limits.

In cases of heating large-diameter billets or when it is necessary to have high production rates, a complex series/parallel electrical connection can be used (Figure 6.13b) with a single large-sized inverter or employing several large-sized inverters (Figure 6.13c).

**Case Study**

**Reader’s Question:** “We plan to induction heat stainless steel hollow bars and one of our supplier plans to build the coils that are supposed to be installed with the same winding direction for all four coils in series with a 50-mm gap and without copper shield plates at the end areas of each coil. Please provide your opinion on the following coil arrangement:

1. CCW–CCW–CCW–CCW or CW–CW–CW–CW (using the same wound coil arrangement: clockwise [CW] or counterclockwise [CCW])

2. CCW–CW–CCW–CW or CW–CCW–CW–CCW (differently wound coil arrangement)"

**Answer:** It is obviously the most cost-effective approach to make identical coils using the same coil winding arrangement (regardless whether it is CW or CCW). This will help reduce a number of spare coils and will not require special coil identification (which coil should be positioned where). However, in some cases, the use of identical coils might lead
to certain challenges. It is particularly the case when heating elongated workpieces (e.g., bars, rods, long billets, strips, ropes, wires, etc.).

For example, consider the case shown in Figure 6.14. There are four in-line coils A through D. Let us first assume that each coil has an identical design (a multiturn solenoid inductor having a helix coil winding). The eddy current induced within the workpiece will have not only a circumferential component of eddy current flow but also a longitudinal component. Therefore, since there would be a longitudinal component of induced eddy current, then there would also be a corresponding induced longitudinal voltage drop $\Delta V$ along the length of the heated workpiece. Figure 6.14 shows that each coil (coils A through D) will induce within the heated workpiece four corresponding longitudinal voltage drops: $\Delta V_A$, $\Delta V_B$, $\Delta V_C$, and $\Delta V_D$. The combined longitudinal voltage drop will be approximately equal to the sum of all four voltage drops:

$$\Delta V_{\text{Total}} = \Delta V_A + \Delta V_B + \Delta V_C + \Delta V_D.$$  

(6.6)

If support/guide rolls positioned at the beginning of the induction line (Ground #1) and at the end of the line (Ground #2) are grounded, then there will be a closed-loop circuit (dotted line), “Ground #1–Roll #1–Workpiece–Roll #2–Ground #2,” and a corresponding parasitic current flow that may result in arcing between bar and rolls. Arcing may lead to several undesirable phenomena. These include but are not limited to the following:

- Negatively affecting the surface conditions of the workpiece and rolls resulting in surface pitting, erosion, and arc marks just to name a few.
- Bearings of the support rolls might fail prematurely.

Some practitioners have attempted to reduce a longitudinal voltage drop using coils with alternating coil turn windings and helix effect. For example, all coils with odd numbers have CW wound turns, but all coils with even numbers have CCW turns.

A better effect can be achieved by using identical conventionally designed coils but having different circuit connections, as shown in Figure 6.15.

Therefore, in a perfect world, if each coil induces a longitudinal voltage drop within the heated workpiece of the same magnitude, then the total longitudinal component of induced voltage will be $\Delta V_{\text{Total}} = 0$. In reality, it will not be equal to 0. This is so because the electromagnetic properties of the heated material (e.g., carbon steel) will change with an increase in temperature and an induced voltage drop within the workpiece will not be the same regardless of having identical coils. Besides, neighboring coils will have different electromagnetic interactions with each other. This will also affect the respected voltage drops per coil. Nevertheless, the longitudinal voltage drop will be dramatically reduced,
and its negative impacts will be substantially lower. Obviously, the complexity of bus bar work is a drawback of this approach. However, the ability to use identical coils is a significant advantage of this approach.

When using coil connections shown in Figure 6.15, one should keep in mind that if coils are electromagnetically short and the distance between coils is less than two coil O.D., there might be a field cancellation in the end areas, resulting in reduced overall electrical efficiency. This field cancellation between coils can be eliminated by using opposite wound coils B and D in Figure 6.15.

A similar effect with respect to a voltage drop reduction can be achieved if one would use identical coils with so-called split coil windings, as is shown in Figure 6.16. Figure 6.16a shows a conventional coil design and instantaneous longitudinal current flow. Figure 6.16b shows a split coil winding design and instantaneous longitudinal current flow for this approach. It is important to make sure that in each case, the instantaneous circumferential coil current orientation is as shown in Figure 6.16c. Thus, even though the longitudinal components of the coil current shown in Figure 6.16b are oriented in opposite direction, the circumferential coil current of all neighboring turns is oriented in the same direction. In this case, overall longitudinal voltage will be minimized and there will be no field cancelation or coil electrical efficiency reduction. Note that split coil windings may be used in progressive/continuous heating, but it could result in “cold” spot(s) in static heating applications.

**Reader’s Question**: “I would like to know where you install copper shield plates. As far as I know, the copper shield end plate is only needed for preventing overheating to steel frame or rolls between coils. Is there any other reason, such as preventing cross-talk between two different inverter outputs?”

**Answer**: There are two general types of copper shield plates (also called end plates): (1) slotted plate (electrically open circuit plate) and (2) unslotted plate (electrically closed

**FIGURE 6.15**
Case study for alternative coil connections. (From V. Rudnev, Two-day workshop on *Induction Heating and Heat Treating Technologies* for Sandvik Materials Technology Group, Sandviken, Sweden, March 20–21, 2014.)

**FIGURE 6.16**
Conventional coil windings (a) versus so-called split coil windings (b). (c) Same instantaneous orientation of circumferential coil current. (From V. Rudnev, Two-day workshop on *Induction Heating and Heat Treating Technologies* for Sandvik Materials Technology Group, Sandviken, Sweden, March 20–21, 2014.)
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circuit plate). The slotted copper end plate has a very minor impact on coil electromagnetic field distribution (Figure 6.17a vs. Figure 6.17b). Slotted end plates are primarily used for mechanical support of the induction coil and to protect the inductor from accidental impact force and abuse. Therefore, such plates do not have any noticeable impact on the prevention of heating of steel frames, support rolls, and other electrically conductive devices located in proximity to induction coil ends.

In contrast, unslotted copper end plates have a dramatic effect on the electromagnetic field of an induction coil (see Figure 6.17c). Their effect is often described as a “robber” ring effect or Faraday ring effect (see Section 3.1.5). Since copper is a good electrical conductor, the electromagnetic field of an induction coil will induce a substantial amount of eddy currents within the copper end plate. According to Faraday’s law of electromagnetic induction (Equation 3.39), an induced current is always oriented in opposite direction to a source current (coil current). Therefore, eddy current flowing within the end plates generates its own magnetic field, which has an opposite direction to the direction of the main coil field, resulting in some eddy current cancellation within the rolls and therefore acting as electromagnetic shields (see Section 4.7.1). This is the reason why it is possible to reduce (but not completely eliminate) not only the heating of rolls located in coil end regions but also the heating of the frame and enclosure at coil ends.

Also, unslotted copper end plates are used in cases where there is substantial cross-talk (electromagnetically speaking) between coils—the cross-talk can be dramatically reduced but might not be eliminated completely.

FIGURE 6.17
Magnetic field distribution using bare coils (a) versus coils with slotted end plates (b) versus unslotted end plates (c). (From V. Rudnev, Two-day workshop on Induction Heating and Heat Treating Technologies for Sandvik Materials Technology Group, Sandviken, Sweden, March 20–21, 2014.)
Keep in mind that since unslotted copper end plates are located in proximity to the induction coil, there will be substantial heat generation within them requiring water cooling. Besides, some reduction in coil electrical efficiency should be expected when unslotted copper end plates are used. Greater coil I.D., shorter coil length, and smaller coil–to–end plate distance all result in more noticeable coil efficiency reduction compared to a bare coil.

6.2.2 Longitudinal and Transverse Cracks

Longitudinal and transverse cracks are often a concern when designing induction systems for heating steels that exhibit low toughness and poor ductility. This includes high-carbon steels (i.e., carbon steel of 0.6% C and higher), as-cast steels, and cast irons. These cracks may appear because of excessive thermal stresses (Figure 6.2b and c), the presence of porosities in cast materials, chemical segregation, as well as other irregularities discussed earlier in Chapter 4. Thermal stresses are caused by thermal gradients [259,549,556]. Experience shows that, in many applications, these cracks occur during the initial heating stage, when the internal areas of the bar are in a nonplastic condition. A “soft” start is required to avoid excessive thermal gradients and cracking that might be associated with them (Figure 6.9b). In other cases, cracking can be promoted by reaching very high temperatures and appear at the final stage of heating.

The use of a combination of relatively low frequencies, modest power densities, and sophisticated process control is a helpful way to reduce “surface-to-core” thermal gradients when heating large-diameter bars and billets.

Typical casting imperfections do not usually have a significant impact on the eddy current flow. Nor do they cause any considerable “hot” and “cold” spots because of a variation in electromagnetic properties of porous areas while using low and medium frequencies. It should be pointed out that when using higher frequencies (e.g., 30 kHz and higher), an eddy current flow deviation and localized temperature surplus attributed to casting imperfections might occur.

6.2.3 Transient Processes and Nose-to-Tail Temperature Profiles

Surface-to-core uniformity is only one of several thermal requirements commonly specified by the customer. Another requirement is the “nose-to-tail” temperature profile of the heated bar. Electromagnetic end effect and transient processes that take place in continuous induction bar heating lines are primarily responsible for the appearance of nose-to-tail temperature nonuniformity. Transient processes include start-up and shutdown phases. Let us consider the shutdown process that takes place when the trailing end of the last bar continuously moves through the induction heater. In this case, the transient end effect takes place, manifesting itself in a noticeable heat source surplus and higher temperatures at the bar trailing end compared to its body.

Figure 3.37 shows the integrated normalized power density distribution along the length of a nonmagnetic stainless steel bar (O.D. = 0.076 m) for different positions of its trailing end inside the induction coil (coil length = 0.28 m; frequency = 5 kHz) while the voltage of the inductor is constant. The dotted curve corresponds to the extreme values of the specific power density in the end zone of the bar. It is obvious that the end zone will be heated to noticeably higher temperatures compared to the regular body of the bar.

With a longer coil and increased frequency, the surplus of heat sources induced within the bar end area will increase. The power density profile and temperature distribution along the bar end area where the end effect occurs are not the same. Because of the
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additional heat losses from the bar butt end and the heat transfer by thermal conduction, the longitudinal temperature nonuniformity is considerable but not as dramatic as the power density surplus.

Temperature distribution within the bar end caused by a transient effect can be quite complex depending on application specifics, including ferromagnetic versus nonmagnetic material, skin effect, single coil versus multicoil design, temperature level, power density, and some other factors. Figure 6.18 shows the temperature profiles resulting from a transient end effect at the leading end of titanium bars with a diameter of 25.4 mm (1 in.) traveling at a speed of 50.8 mm/s (2 in./s) using a frequency of 30 kHz.

FIGURE 6.18
Transient end effect during processing of titanium bars of diameter of 25.4 mm (1 in.) through induction line consisting of three coils.
Obtaining the required temperature distribution along the length of long products that travel one after the other with a considerable air gap requires managing the transient end effect. In the case of heating nonmagnetic materials (i.e., certain stainless steels, titanium, or carbon steels heated above the Curie point), there is typically a surplus of induced power in the bar end area. Higher frequency, more intensive heating, and a larger axial gap between bars lead to a greater surplus of heat sources generated in its end areas.

In contrast, the end effect in magnetic bars has several features compared to the nonmagnetic one. As discussed in Section 3.1.7, the electromagnetic end effect in ferromagnetic materials is mainly affected by two factors: the demagnetizing effect of eddy currents, which tends to force the magnetic field out of the bar, and the magnetizing effect of the surface and volumetric currents, which have a tendency to gather the magnetic field within the bar.

The first factor causes an increase of induced power at the bar’s end (similar to the end effect of a nonmagnetic bar). The second factor causes a power reduction at the bar’s end. Therefore, the ends of ferromagnetic bars, even inside a long inductor, may be either overheated or underheated compared to its neighboring region. Studies show that the power deficit causing an underheating of the end area will be pronounced for high-magnetic permeability steels that are heated with relatively low power densities and frequencies. However, the heat surplus of the bar end is more typical.

Power density distribution within the bar end region undergoes a continuous change as the bar passes through the IH line, becoming more complex. In some cases, it can have a unique wave-shaped power distribution along the bar length, having a local surplus of power at the end of the bar; however, in the region adjacent to the end, there will be a power deficit compared to the power induced in the body of the bar.

The transient end effect in the bar end zone is similar to the end effect during static heating; however, there are several features that make this process unique and must be taken into account when designing IH lines. One of the main features deals with the variation of coil current (in the case of constant coil voltage) or coil voltage (in the case of constant coil current) or both (in the case of constant or regulated coil power) when the leading end of the first bar or trailing end of the last bar moves through the induction coil (assuming that the remaining bars travel end to end or with a sufficiently small axial gaps).

In addition to the transient electromagnetic end effect, there is also a transient thermal effect. During the start-up of a cold line, the transient thermal effect is also quite complex because of the fluctuating temperature of the refractory and the impact of radiation view factors. The start-up begins with a cold refractory (or, in the case of an intermediate start, the refractory is partially heated/cooled). It leads to a deviation of heat losses from the bar surface owing to thermal radiation and convection.

In addition to the temperature nonuniformity that occurs in the areas of the leading end of the first bar and trailing end of the last bar, there might be other situations that would result in the appearance of nose-to-tail temperature nonuniformity requiring a special process control recipe.

When bars travel end to end through an IH line, the nose-to-tail temperature uniformity is typically not a problem (excluding the first and the last bars of the group). However, in real-life conditions, there is often a 0.05–0.1 m (2–4 in.) or larger air gap between the leading and following bars. The existence of these appreciable size axial gaps could result in noticeable axial temperature nonuniformity, particularly in the bar end region.

The task of obtaining nose-to-tail temperature uniformity is typically a more difficult one compared to minimizing the surface-to-core temperature gradient. Clear understanding
of the intricacies of the process and applying a sophisticated control algorithm can significantly minimize the nose-to-tail temperature nonuniformity.

6.2.4 Energy Efficiency of In-Line Cylinder Bar and Rod Heaters

IH manufacturers pay special attention to the maximization of energy efficiency. Coil efficiency is often a measure of the effectiveness and competitiveness of an induction system. Among other factors, electrical efficiency is a complex function of several design parameters including coil-to-workpiece radial gap (electromagnetic coupling), physical properties of the heated material, length of the coil, and applied frequency. Figure 6.19 indicates that there will be high coil electrical efficiency $\eta_{el}$ when the frequency corresponds to a solid cylinder O.D.–to–δ ratio of greater than four (O.D./δ > 4). The use of a frequency that results in O.D./δ > 10 will only slightly increase the $\eta_{el}$ but might noticeably increase surface heat losses and reduce thermal efficiency.

The use of very high frequencies (frequency > F2) tends to slightly decrease the total efficiency owing to higher transmission losses and high surface heat losses as it will require a longer heat/soak time to provide the required surface-to-core temperature uniformity. If the chosen frequency results in O.D./δ < 3.2 (frequency less than F1, Figure 6.19), the coil efficiency will dramatically decrease. This is attributed to the cancellation of induced eddy currents circulating in the opposite sides of the solid cylinder. Table 6.8 shows minimum bar/billet diameters as a function of frequency and temperature for efficient IH of selected metals.

![FIGURE 6.19](image)

Coil electrical efficiency $\eta_{el}$ versus the frequency when heating solid cylinders.

**TABLE 6.8**

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C/°F)</th>
<th>Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.06</td>
<td>0.2</td>
</tr>
<tr>
<td>Copper</td>
<td>900/1652</td>
<td>68</td>
</tr>
<tr>
<td>Aluminum</td>
<td>500/932</td>
<td>68</td>
</tr>
<tr>
<td>Brass</td>
<td>900/1652</td>
<td>102</td>
</tr>
<tr>
<td>Titanium</td>
<td>1200/2191</td>
<td>304</td>
</tr>
<tr>
<td>Tungsten</td>
<td>1500/2732</td>
<td>168</td>
</tr>
<tr>
<td>Steel</td>
<td>1200/2192</td>
<td>253</td>
</tr>
</tbody>
</table>
It is typically required that an IH line processes bars of several different diameters. The specified cross-section range to be processed in a given set of induction coils and how many coil sets are needed requires consideration of a number of factors and also affects the overall energy efficiency of the system. The coil heating efficiency is largely a matter of the fill factor (area of the workpiece to be heated compared to the inside area of the coil windings). As the fill factor decreases, the efficiency decreases, requiring more power at coil terminals and increasing its water-cooling needs.

On the other hand, the savings in energy cost because of increased coil efficiency by using a number of dedicated coil sets that are designed for heating a certain range of workpiece sizes is diminished by the capital cost of investing in several sets of coils. There is also some production loss associated with the time required to change coil lines, although advanced quick change design features can minimize this downtime.

A careful analysis of the product mix is necessary to determine how often the bar size may change and what the duration of each product run will be. These answers will help the user to determine the value of a second and possibly a third coil set. Note that, below the Curie point, the heating efficiency is not as greatly affected by the electromagnetic coupling; thus, it may be worthwhile to consider changing only the so-called above-Curie coils when running different bar sizes.

In some cases, the smallest bar size, which results in poor coil-to-bar fill factor, might represent less than 5% of the total production mix. Therefore, in such cases, it might be cost-effective for the customer to use the coil set designed for heating “big runners” to heat the small size bars as well, which under normal conditions would require additional coil sets. This is so assuming that severe current cancellation does not occur (review a case study shown in Figure 4.71).

Additional sets of coils will be of little or no value if they are not readily available when needed. They must be stored in a designated area of the tool crib and properly identified as to the size of the bars they will process, the direction of bar flow through the coil, and, in some cases, their position on the coil line (assuming there are several coils in-line).

In most instances, frequency selection when specifying an induction bar heater is a compromise because bar processing companies can rarely utilize a dedicated bar size with a particular IH system. As a consequence, it is often necessary to heat a bar that is too large or too small for a single frequency and therefore the efficiency of the induction machine suffers. Some of the solid-state inverters lend themselves to a dual-frequency configuration for the load circuit that, to a large extent, can overcome this problem. A typical example would be for a heater to be able to operate at 10 and 3 kHz or 3 and 1 kHz. Such approaches typically require installing dual capacitor banks. A detailed discussion of solid-state power supply design is provided in Chapter 7.

A dual-frequency design concept of an induction bar heater allows one to improve the overall efficiency. This concept utilizes a low frequency in the initial heating stage, when the bar retains its magnetic properties. In the next stage, when the bar becomes nonmagnetic, it is more efficient to use a higher frequency to avoid current cancellation.

If the product range (variety of bar/rod sizes) is too great, the ability to properly guide the smaller bars may be jeopardized. This can lead to jam-ups, unacceptable temperature nonuniformity at the given production rate, and excessive scale formation, which have a negative impact on the maintenance cost, equipment life, and operation.

The specifics of IH rectangular, trapezoidal, and round-cornered square (RCS) bars are discussed later in this chapter.
6.3 Billet Heating

6.3.1 IH of Steel Billets

The goal of IH of steel cylinder billets is to raise the billet temperature to the level where it is plastic enough to be forged or extruded or to employ other processes involved with plastic deformation. The target temperatures are typically in the range of 1050°C (1922°F) to 1260°C (2300°F) depending on the steel chemical composition and specifics of the postheating processing. The required surface-to-core and nose-to-tail temperature uniformity in billet heating applications is commonly ±20°C to ±30°C.

Depending on the size of the billet, the heat time ranges from dozens of seconds (for smaller billet sizes) to dozens of minutes (for large billets). The most typical range of frequencies is from 500 Hz up to 10 kHz, depending on the geometry of the billets. Smaller-sized steel billets (e.g., less than 13 mm [½ in.] diameter) call for higher frequencies (>30 kHz). Lower than 500-Hz frequencies can be used for larger billets (0.2 m/8 in. diameter and larger). There are two commonly used heating modes in induction billet heaters: progressive heating and static heating (Figure 6.6).

6.3.1.1 Progressive Heating of Billets

6.3.1.1.1 Profiled Coils

In the progressive multistage heating, billets are moved end to end through a single coil or multicoil induction heater. Multiturn solenoid-type (helical) coils are almost exclusively used in billet heating applications.

In single-inductor applications, the surface-to-core temperature uniformity can be improved or the needed coil length can be shortened when profiled (also referred to as “graded”) coils are used instead of conventionally designed inductors with uniform winding. As shown in Figure 6.20, the main feature of profiled designs is the nonuniform winding (variable pitch) of the copper turns along the coil length.

The winding of coil turns for the initial and intermediate heating stages is much tighter than that for the final heating stage. In addition, narrower face copper tubing can be used, further increasing current density. This results in accelerated heating to produce an intense radial heat flow into the billet’s core during initial and intermediate stages of heating as compared to utilizing a conventional coil design with uniformly wound turns. After the billet surface reaches a maximum permissible temperature, the heat intensity is reduced to the levels that compensate for heat losses from the billet’s surface (owing to radiation and convection) and heat conduction toward the colder core (Figure 6.9a vs. Figure 6.8a). Loose coil windings in combination with wider coil copper tubing can be used at the final heating stage (Figure 6.20b) to reduce heating intensity.

Obviously, the process of fabrication of the profiled coils is more complex, labor intensive, and time consuming compared to a conventional design. One of the main concerns when using profiled coil designs deals with the necessity to avoid excessive surface-to-core temperature gradients during the initial heating stage that might result in crack initiation when heating some alloy steels and, particularly, high-carbon steels or cast metallic materials. Thus, an increased number of coil sets might be required to properly address issues associated with low-toughness materials (Figure 6.9b). This is an obvious drawback of graded inductors. However, the advantages gained may compensate for the extra cost.
The recommendations discussed in the previous section regarding frequency selection in bar heating applications hold true in billet heating as well. A quick rough estimate of the required power was described in Section 3.3.1. More accurate calculations can be done using numerical computation (see Section 3.4) that is obviously the preferable method since it allows one to predict more accurately how different factors may influence the transitional and final heating conditions of the billet and what must be accomplished in the design of the IH system to improve its effectiveness and guarantee the desired heating results [550–554].

As an example, Figure 6.21 illustrates the results of numerical computer modeling, showing the steady-state temperature profile and magnetic field intensity distribution along the length consisting of four carbon steel billets having sufficiently small axial gaps [85,548]. The billets are indexed using a pusher system one after the other. Most of the time, the billets are immobile in the inductor and move only when the leading billet reaches the required thermal conditions and exits the coil and a new billet is loaded.

The parameters of the induction system are as follows:

- Billet geometry: O.D. = 0.08 m, length = 0.23 m
- Coil geometry: I.D. = 0.152 m, length = 0.99 m, number of turns = 50
- Refractory: thickness = 0.02 m, thermal conductivity = 0.028 W/°C
- Frequency = 2.4 kHz

---

**FIGURE 6.20**
Conventional (a) and profiled (b) coil windings.
Induction Mass Heating

The distribution of magnetic field intensity and temperature along the billet length is formed by several electromagnetic and thermal phenomena. This includes the longitudinal end effect, thermal edge effect, edge effect of joined materials, and some others. Because the nature of these effects has been discussed in detail in Section 3.1, it is assumed that the reader is aware of these phenomena. Here, we only briefly review a case study and the general tendencies of the appearance of these effects and their influence on the process of induction carbon steel billet heating using Figure 6.21 as an example.

6.3.1.1.2 Electromagnetic End Effect on Billets

The magnetic field in the tail end of billet #1 is formed by the end effect of a ferromagnetic body. In this case study, the electromagnetic end effect results in the localized heat deficit of the tail end of billet #1 (0 < Z < 8 cm).

In the area where billet #1 (heated below the Curie temperature) is brought into contact with billet #2 (the surface temperature of this billet exceeds the Curie point), the electromagnetic effect of joined materials with different properties (Figure 3.46) takes place. The magnetic field intensity at the central parts of both billets is approximately the same, meaning that the EMF at the central parts of these billets is close to homogeneous. However, at the area of the ends of billets having a sufficiently small gap, a noticeable distortion of the EMF occurs.
At the tail end of billet #2 heated above the Curie point, the magnetic field intensity and power density are sharply increased. In contrast, magnetic field intensity and power density are sharply decreased in the leading end of ferromagnetic billet #1. The initial axial temperature distribution of billet #2 was not uniform. An increase of power density in the tail end of billet #2 will approximately compensate for its initial heat deficit.

The effect of the joined materials also takes place at the area where billets #2 and #3 as well as billets #3 and #4 are brought into contact. The temperature of all three billets is above the Curie point; thus, the $\mu_r$ of these billets is equal to 1. At the same time, the electrical resistivities of these billets are different to some degree because they are heated to different temperatures. Therefore, the different electrical resistivities result in only minor variations of the magnetic field intensities and power densities leading to slight heat deviations (minor ripples in temperature distribution).

### 6.3.1.1.3 Thermal Edge Effect in Billets

Two counteracting effects affect the temperature distribution at the leading end of billet #4: the electromagnetic end effect of the nonmagnetic body and the thermal edge effect. The thermal edge effect takes place because of Lambert’s law (cosine law). According to this law, the thermal radiation is not only a function of the kind of metal, its surface condition, and temperature but also a function of the workpiece shape and surroundings. The thermal edge effect can be taken into account by standard computation procedures applying radiation shape factors (also referred to as view factors or angle factors).

As shown in Figure 6.22, the thermal edge effect takes place in the trailing end (left end) of billet “A” as well. The thermal radiation losses are a function of the fourth power of temperature. Therefore, since the temperature of billet “C” is much higher than the temperature of billet “A,” the thermal edge effect in the end area of the billet with higher temperatures (at the final heating stage) is noticeably greater compared to the thermal edge effect during the initial heating stage.

As one can see from Figure 6.21, a surplus of power induced in the area of the leading end of billet #4 only partly compensates for the thermal edge effect, resulting in a local heat deficit. A uniform temperature distribution along the length of billet #4 that is located in the final heating stage may be achieved by properly choosing the parameters of the induction system, such as coil overhang, frequency, and so on.

### 6.3.1.1.4 Axial Heat Flow

Since billets located in different heating positions have different temperatures, one of the key questions in modeling an induction billet heater is how to consider the heat flow in the axial direction (i.e., from billet “A” to billet “B”; Figure 6.22). Realistically, the butt end surfaces of billets are never perfectly smooth. Instead, the surface roughness, presence of oxide layer, and scale provide a major impact on the axial heat transfer through the contact area of two billets. There are two principal contributions to the heat transfer in the area of the contact:

- The heat flow through the air pockets
- The thermal conduction through the solid-to-solid point-wise contacts

The first factor represents the major thermal resistance to heat flow through the contact area, because the air is a poor thermal conductor. The experience of modeling induction billet heaters shows that from an engineering perspective, it is appropriate for the majority
of forging applications to assume that the heat flow through the contact area of two billets is insignificant. If required, a quick estimate of the heat transfer can be conducted using a method based on the thermal contact resistance approach discussed in Ref. [607].

6.3.1.1.5 When Coil Change Is Required

Efficiency, system availability, and flexibility are important factors that should be taken into consideration when evaluating the performance of an induction billet heater. As mentioned in Section 6.2, the efficiency is largely a matter of the coil’s fill factor (assuming that eddy current cancellation does not occur). In some cases, this results to utilizing several sets of coils in order to minimize the coil-to-billet radial gap and maximize the heating efficiency. The ability to keep the production loss because of the time required to change coil sets to a minimum is essential. Quick-change coil capability allows shortening the change over time to minutes, resulting in a reduction of lost production time.

When frequent coil change is required, the twin track design is beneficial (Figure 6.23). With this approach, an induction billet heater integrates a twin track with a common base support to simplify the changeover operation and also eliminate the need for offline storage space. In this case, complete coil lines are stored on a parallel track that is in direct alignment with the operating coil assembly. Most are twin track systems housing two assemblies but can be designed to be capable of housing several assemblies.
6.3.1.1.6 Power Profiling

One of the most frequent causes of downtime with induction heaters of steel billets is coil breakdown to earth. This is usually caused by scale particles finding their way to the copper turns and causing the arcing (flashover) and copper turn water leaks. As a result, permanent damage to the coil can occur and the power supply trips.

The majority of induction heaters for small- and medium-sized billets utilize a multi-stage heating mode where billets are moved end to end through a single coil or through multiple coils by means of one of the basic billet feed systems: pinch roll drive, pusher, walking beam, or robots [605].

Conventionally designed billet heaters comprise a single large inverter or several large inverters powering an entire coil line (Figure 6.7c). The coils could be connected electrically in a series or parallel or in a combination of both, depending on the type of power supply (Figure 6.13). The type of power supply, its load-matching capability, and the necessity to avoid voltage or current limits primarily affects the choice of coil connection. Such circuit connections are inevitably associated with restricted process controllability, because control of power cannot be localized to a particular coil but rather to a number of inductors that comprise a particular circuit [245].

The specifics of power distribution along the induction line have a vital impact on internal heat uniformity. The industry uses different rules of thumb to promote desirable distribution of power along the heating line. Some frequently applied rules are 60:40 and 70:30 rules [188]. For example, a 60:40 rule indicates that 60% of total power should be distributed within the entering half of the induction line. The remaining 40% is applied to the exiting half of the line. According to such rules, intense heating occurs in the first half of the line, developing an intense heat flow toward the workpiece’s internal regions and its core.

After the workpiece’s surface reaches sufficiently high temperatures, the heat intensity is reduced. Energy supplied to the second half of the heating line is substantially lower. The heat generated within the second half of the induction line results in only modest rise of the surface and subsurface temperatures, promoting heat soaking toward the core. Induced power primarily compensates for a heat transfer toward the colder core and balances the thermal surface losses. Since an induction heater usually provides heating of
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a number of bar/billet sizes, power distribution along a conventionally designed line is selected based on the most power-consuming production run.

6.3.1.1.7 Subsurface Overheating

In some cases, shifting the majority of power into the entering half of the heating line is associated with several obvious advantages; however, in other cases, it could be associated with certain drawbacks related to cracking of brittle materials, subsurface overheating, and limited process flexibility.

Pyrometers can only reliably measure the temperature at certain spots of the workpiece’s surface. Regardless of the fact that the surface temperature may be within the typical range required for hot working operation (±20°C–25°C or so), the internal heat distribution, being outside of that range, might be quite different. Local subsurface heat surplus or deficit may occur. None of the workpiece areas should reach extremely high (permanently damaging steel) or low (negatively affecting the process of hot working and its equipment) temperatures. Thus, it is imperative to know the thermal conditions everywhere within the billet.

Since internal temperatures cannot be easily measured or even seen, they can only be simulated mathematically. Therefore, precise temperature monitoring using advanced computer modeling to obtain a reliable prediction of temperature distribution within the workpiece is imperative in designing modern induction billet heating systems.

Development of application-oriented software is an important step in the process optimization of modern induction heaters. Highly technical and specialized software utilizing numerical simulation techniques such as finite elements, edge elements, finite differences, finite volumes, boundary elements, and others is an essential part of the package of a modern IH system. These numerical techniques provide substantially more accurate and detailed information regarding the selection of process parameters, coil design specifics, and the resulting internal temperature distribution. The results of simulations can be loaded into a recipe inside a programmable logic controller (PLC) to operate the heater.

Besides the potential danger of premature die wear of hammers and presses, improperly heated billets can raise some safety concerns when forging workpieces that have appreciably higher subsurface temperature and can also cause problems related to the quality of hot worked parts. As discussed in Sections 3.1 and 6.1.4, if surface or subsurface steel burning occurs, its properties cannot be restored by heat treating or subsequent mechanical working, ultimately requiring scrapping the products. All these emphasize the importance of computer simulations as a means to accurately predict internal thermal conditions and to provide information for developing an optimal strategy for dynamic redistribution of power along the heating line as a function of a particular production run. It also highlights a limitation and a danger of using some conventional software and process control strategies that predict only the rise of average (mean) temperature or the temperatures of the surface and the core of the billet.

Assuring the proper thermal conditions of heated materials that cannot be measured or even seen is only one reason that necessitates using advanced mathematical simulation. When designing an IH system, there is always some degree of uncertainty associated with real-life deviations present in different production runs. Computer modeling helps assess particular real-life process disturbances, quickly analyze a specific technological situation, and develop a process control strategy utilizing computational intelligence, statistical methods, and nonlinear mathematical optimization to assure accomplishment of production goals [475].

The possibility of billet sticking (Figure 6.24a) rises when the billet temperature exceeds 1260°C (2300°F) and is typically related to surface or subsurface heat surplus and can be
further aggravated by a substantial pushing force producing a diffusion bonding effect between two billets heated to sufficiently high temperatures being in a contact.

Since diffusion intensity increases with temperature, it is much easier for diffusion-driven processes to occur when higher temperatures are reached. Therefore, the presence of heat surplus increases the probability of billets to be stuck/fused/welded/bonded together. Applied pressure for pushing billets worsens the probability of this problem to occur. Theoretically speaking, there are some additional factors that might trigger an appearance of the billet-sticking problem. This includes the pitch of coil turn windings (helix effect, see Section 3.1.7.2) and the size of copper turn tubing. Larger values of these parameters result in greater axial/longitudinal component of eddy current flow, which, in turn, may manifest itself in arc development between neighboring billets. However, the impact of these phenomena is much less pronounced when heating steel billets compared to the presence of high temperatures and substantial pushing pressure.

There is a common misassumption that with IH of steel billets and bars, the coldest temperature is always located at the core and that the maximum temperature is always located at the surface [187,188,485]. Therefore, it is assumed that overheating does not occur if the surface temperature measured by a pyrometer does not exceed the maximum permissible level.

It is important to recognize that, under certain conditions, the heat losses from the surface of the billet can shift the temperature maximum further away from the surface, marking its location somewhere beneath the surface. The location and magnitude of subsurface overheating is a complex function of four major factors: frequency, refractory, final temperature, and power distribution along the heating line [36,608].

Lower frequencies increase the δ, producing deeper heating that is usually associated with more intense temperature rise at the internal regions of the billet. This shortens the heating line but can also shift the location of the maximum temperature further away from the surface.

An increase in forging temperatures also causes a shift in the positioning of the maximum temperature further from the surface and deeper toward internal regions.

The use of a sufficiently thick refractory with good thermal insulation properties does just the opposite: it reduces subsurface heat surplus and shifts the maximum temperature of the billet toward the surface.

The effect of power distribution along the multicoil heating line on the billet’s temperature distribution is more complex [187,188,485]. Applying more power up front may appear to be a universal remedy since it generates more energy into the billet at the front of the
heating line, permitting more time for heat transfer into the core and shortening of the length of the line. This approach may use a single inverter that powers several coils with a graded number of turns or appropriate coil circuit connections (e.g., Figure 6.7c) [36,608]. In cases like these, the power distribution along the heating line cannot be easily modified when the production rate, alloy grade, or billet size changes. For example, if the production rate is reduced, the subsurface temperature surplus typically worsens with a conventionally designed line. This can manifest itself as a billet sticking (discussed above) when the subsurface temperature becomes hot enough to cause the billets to fuse together (Figure 6.24a). Figure 6.24b shows billets that were stuck together in the subsurface area and not at the surface.

This billet sticking problem is more noticeable with graded power distribution along the induction line when the system runs at a rate slower than for which it was designed. Because the system puts more energy into the billet in the beginning of the heating line, excessive energy transfer into the billet's internal areas occurs when the line runs slow. The existence of surface heat losses can reverse the normally expected radial temperature profile, leading to the subsurface temperature being greater than at its surface.

**Case Study** [187,188,485]. An induction system for heating 0.064-m-diameter carbon steel billets at a production rate of 2500 kg/h is made up of three in-line coils connected electrically in series and fed from a 1-kHz inverter (Figure 6.25).

All coils have an identical design. Figure 6.26 shows surface-to-core profiles. Figure 6.26a shows processing 0.051-m-diameter carbon steel billets at a slower rate and Figure 6.26b shows surface-to-core profiles when processing larger-diameter (0.064-m-diameter) billets at a nominal rate [187,188,485]. Note that, in both cases, the surface temperature that would be recorded by a pyrometer is the same. Further reduction in the diameter of the billets or production rate could further worsen the severity of subsurface overheating that can manifest itself in billets sticking (Figure 6.24a) as well as grain boundary liquation/incipient melting (Figure 6.24c) and intergranular cracking (Figure 4.39). Therefore, attempts...
should be made to develop a process control strategy that will avoid an excessive surface/subsurface heat surplus generation.

Optimization of steady-state processes is a prime goal of designing induction billet heaters. At the same time, optimization of the transient processes is also an important part of an overall optimization strategy.

Transient processes include start-up (including cold-start and warm-start) and shutdown states as well as standby or the holding state that occurs during the unexpected downtime of the hot working machinery. Over the years, a variety of techniques have been developed to optimize transient processes [544–547]. For example, Newelco (presently Inductotherm Heating & Welding Ltd., UK) has developed an impressive technique for handling prolonged standby conditions. Newelco billet heaters were specifically designed to minimize the disruption of metal plastic deformation machinery caused by the inevitable occasional break in activity such as needed press adjustments or die changes. Unique coil design minimizes the gap between neighboring coils to approximately 12 mm, which is an important design feature when there is a requirement to hold hot billets inside the induction heater for a prolonged time. In order to do so, the coil voltage is reduced to the level that will compensate the surface thermal losses of the billet located in the second billet from the coil exit. The axial temperature distribution along the heating line can be kept for an extended period, so that when the heater is restarted, only the first billet is below the needed forging temperature range. Obviously, this is only one of the possible approaches to optimizing the standby state of the billet heater, and its recipe can be modified to meet the requirements of the particular application.

6.3.1.2 Maximizing Flexibility of Induction Billet Heaters

In a modern, highly dynamic and globally competitive market place, it is important not just to build a fully automated system but a system with advanced process flexibility that allows quick adjustment to a rapidly changing business environment [36,227,485]. One way
to maximize the flexibility of induction heaters, while ensuring the highest heating quality and optimizing heating parameters for a wide range of warm and hot working applications, is by applying modular IH technology. Inductoheat, Inc. was the first company that developed and implemented modular induction heaters.

As an example, Figure 6.27 shows one such design—Inductoforge style billet heater, which allows adjusting not only the power but also the frequency of each heating module within the range of 500 Hz to 6 kHz. This helps optimize heating of a variety of forged billet sizes and materials, permitting modification of the heat intensity and the depth of the heat generation along the heating line depending on specifics of the production run. For example, if the production rate is reduced, a subsurface temperature surplus typically worsens with a conventionally designed line.

Modular systems allow for intelligent 3-D redistribution of electromagnetic heat generation. This maximizes process flexibility for the entire induction line, truly optimizes heating parameters for a wide range of applications, and ensures heating quality.

For example, if today’s market situation requires heating larger billets (e.g., 0.115 m/4½ in. diameter), then a lower frequency (e.g., 500 Hz) produces deeper heat generation and minimizes needed heat time, providing improved surface-to-core temperature uniformity. If the market situation changes tomorrow, demanding heating of smaller-sized billets (e.g., 0.03 m/1¼ in.), then appropriate inverters can be reconfigured, producing higher frequencies (e.g., 6 kHz). This allows reducing $\delta$ when running smaller-diameter billets by avoiding eddy current cancellation, maximizing heating efficiency, and minimizing energy consumption. Since each coil can be controlled individually, the power distribution along an entire heating line can also be optimized for particular production run specifics. In the case of high-production run, more power can be shifted to the cold end of the heating line. If the line is running slow, the maximum power can be distributed closer to the hot end of the line, increasing the efficiency of the heater and improving thermal conditions and quality of heated products.

Development of temperature profile modeling software included in an equipment package represents a measurable step in providing the metal-working industry with smart induction billet heaters. Application-oriented software of the Inductoforge modular induction heaters generates the power settings for each inverter, which can be downloaded into a PLC recipe and predict the internal thermal conditions of heated workpieces.

Some modular designs consist of a high-power rectifier and a number of smaller-sized inverter sections that convert supplied DC input into elevated frequency AC outputs. Unfortunately, such designs have several drawbacks compared to the Inductoforge approach. One of the obvious drawbacks is related to the simple fact that if a single
high-power rectifier section is down, then an entire line is down, leading to downtime and a loss of production. In contrast, with the InductoForge approach, even if any single module is down, the line can still run at a lower rate, which also reflects superior flexibility.

While the coil and power module are the basic components of the Inductoforge modular system, there are several others that complete it. A heavy-duty in-feed tractor or pinch-roll drive system is mounted on top of the cabinet for pushing the billets through the induction coil(s), as well as a heavy-duty extraction system (Figure 6.27). The PLC, HMI (Human Machine Interface), and other controls are mounted on a pendulum, allowing the operator to easily view the monitor. The iHaz™ temperature profile modeling software enables advanced temperature monitoring of the heating process. This software does not just simulate electromagnetic–thermal processes, it also takes circuit analysis and load-matching capabilities of a particular style of semiconductor power supply into consideration. This includes the possibility of reaching “hard” limits that restrict the amount of power that can be delivered (e.g., TOT limits, etc.). Thus, it allows the user to customize a billet temperature profile to best suit parameters and set points that are stored as a recipe/protocol in the PLC.

One cost-effective feature of the Inductoforge modular design is its standardization. It is easier to standardize models across the platform. This allows the modules to be mass produced, greatly reducing the cost, decreasing the amount of spare parts, and providing an ability to swap components (if required). Unique process specifics might demand some specific requirements. As an example, Figure 6.12 shows a variation of the Inductoforge modular induction system for heating long steel bars where each inverter supplies power for two in-line coils.

If an interruption occurs during normal running, when everything has reached steady-state conditions, it is easier to develop strategies to control the heating line. However, equilibrium is not reached until the heater has been running for some time. The complexity amplifies when starting and stopping of the line occur during an unsteady run. Some of the factors responsible for the intricacy relate to a challenge in predicting the thermal state of the refractory, the electromagnetic transient end effects, and 3-D temperature distribution along the heating line. Modular design and developed know-how allow for optimizing transient process stages (unsteady runs), minimizing energy consumption, downtime, and metal loss, while ensuring required thermal conditions of heated workpieces and enhancing equipment flexibility [36].

Unplanned downtime, commonly referred to as “lost opportunity cost,” can greatly affect the profitability of an operation. Conventional designs can perform efficiently when running at the normal production rate. The modular system can be utilized to maintain a high efficiency within the range of runs, including various rates or when heating different steel grades. Longitudinal and transverse cracks might be a concern when heating brittle and low-toughness/ductility alloys (i.e., high-carbon steels, tool steels, cast steels, etc.) or when geometrical irregularities are present. These cracks might appear as a result of excessive thermal stresses that take place when thermal gradients exceed the permissible levels (Figure 6.2c). Safe levels of thermal gradients that would allow the avoidance of cracking are dependent on the metal chemical composition, prior microstructure, billet’s size, temperature, presence of discontinuities, porosities, stress raisers, and so on. Modular design allows for avoiding cracking thanks to an ability to apply a “soft” start condition, when lower-than-normal power densities are used during the initial stage of heating materials that are prone to cracking. A “soft” start requires certain flexibility for the induction system and cannot be easily achieved with conventional designs utilizing a single power supply that provides power to an entire heating line.
Space does not permit reviewing all process control subtleties while handling different transient stages (including cold, warm, or hot start-up, shutdown, standby, and others). Ref. [36] provides a thorough analysis of process control of transient stages.

6.3.1.3 Static Heating of Billets

Progressive multistage horizontal heating is popular for small- and medium-sized metallic billets (usually less than 0.15 m in diameter). At the same time, there are applications where it is advantageous to use a static mode of heating instead of a progressive multistage mode or a combination of both progressive and static heating modes.

One should not be under the impression that it is advantageous to use vertical coil arrangements only when heating large-diameter billets. In some cases, application specifics make static heating a preferable choice over progressive systems even when heating small- and medium-sized billets; some examples of such system will be discussed later in this chapter.

When heating large-diameter steel, Ni-based superalloys or titanium billets (0.2 to 0.3 m or 8 to 12 in. and larger), it is often advantageous to use static heating with a vertical coil arrangement or a combination of the progressive multistage horizontal method for pre-heating and the static vertical method for final heating.

There are several reasons why, in some applications, there is a tendency to use vertical inductors instead of horizontal coil arrangements for static heating large-diameter steel billets. Some of these are outlined below [526,610]:

- Large-diameter billets (e.g., 0.2 m and greater) are relatively long (usually 0.5 to 1.5 m, or 20 to 60 in.), meaning that such billets are quite heavy. Therefore, it is necessary to provide sufficient mechanical support for such heavyweight billets. When using a horizontal coil arrangement, heavy billets cannot be simply placed on a thermal refractory because they will crush it (unless coils are relatively short and billets are rested on rolls located between coils, similar to heating long bars or applying oscillating heating, which will be discussed later in this chapter). In addition, if horizontal coils are used to heat large-diameter billets, there is a challenge to install some kind of support liners inside the inductor; for example, stainless steel liners/rails (water cooled or not water cooled) can be positioned between the coil refractory and billets over the length where support is needed. In this case, there is a challenge to offer reliable, sufficiently strong, wear-resistant, and long-lasting liners that can provide the required mechanical support for heavy billets located inside horizontal induction coils.

- In order to achieve sufficient surface-to-core temperature uniformity, large-diameter billets require longer heating times compared to small- and medium-sized billets, even when lower frequency is applied. Longer heating times are needed for thermal conduction to assure sufficient heat transfer toward a billet’s core. If water-cooled rails are used to provide a support for large billets in horizontal induction systems, then there is a danger of localized cold spots appearing in areas where the hot billet contacts water-cooled rails for an extended period. This could negatively affect the billet’s temperature uniformity around its perimeter.

- A “chimney” effect is also more pronounced when heating large billets. Its appearance in horizontal inductors could produce areas with heat deficit and heat surplus.

- Large billets being heated to high temperatures can sag to a measurable extent because of their considerable weight.
• Some applications demand a specific surface condition of the billets. The surface condition of heavy billets could be altered when they are pushed/dragged through a horizontal induction coil during loading–unloading operations.

• When heating different diameters, the majority of billets will be located nonsymmetrically inside of a horizontal inductor (the axes of symmetry of the billet and coil do not coincide). This causes the electromagnetic proximity effect to be more pronounced (in particular when using electromagnetically short inductors), attributable to an additional heat deviation along the billet perimeter and particularly at its end areas.

In many cases, a vertical coil arrangement eliminates a majority of the abovementioned drawbacks and challenges of horizontal induction systems, providing better reliability and robustness and improving quality when heating large billets. For example, with the vertical coil arrangement, it is not necessary to position the support liners between the coil refractory and billet.

In vertical systems, billets are typically loaded (charged) using a mechanism that is located below the platform with a vertical induction coil. During the loading operation, billets are transferred (e.g., by a trolley conveyor or other means) into a horizontal cradle that is located under the coil. This cradle forms part of a rocking hanger, which pivots 90° and sets the billet vertically over a charging jack, which raises the billet vertically into the inductor. It moves through its full travel so that the lower end of the billet is located at the desirable position inside the coil. The billet’s upper end is positioned in the zone where the coil taps are located, adjusting the coil upper overhang and controlling end effect with further help of a magnetic flux extender. Therefore, in the heating position, the billet simply rests on a specially designed, well-supported thermal pedestal. Sophisticated design and proper handling of the electromagnetic end effect compensate for some heat conduction toward a pedestal.

Such an arrangement allows proper positioning of billets in both radial and axial directions inside the induction coil, achieving better temperature uniformity along the billet’s length and perimeter.

Vertical systems easily allow for compensating the chimney effect by closing the top portion of the inductor using a refractory. They also permit significantly improved coil-to-billet electromagnetic coupling, because it is possible to have substantially smaller coil-to-billet gaps, resulting in higher electrical efficiency and lower coil copper losses and energy consumption (less coil water-cooling requirements), and reducing coil currents and the magnetic forces experienced by coil turns.

It is instructive at this point to provide an example of an induction billet heating installation for the extrusion of carbon steel and stainless steel tubes. This classical system was built by Inductotherm S.A., Belgium (previously called Elphiac) [606] and has a total power rating of 33,000 kW. The billet heater was built for a manufacturer of seamless extruded steel tubes.

The surface of the steel billets is coated with a viscous glass film that acts as a lubricant during extrusion. It is important to take this coating into consideration when designing IH equipment, because it drastically affects the heat losses from the billet surface.

The tube works comprise two production lines [606]:

• One line with a 2000-ton press extruded 120 billets per hour and produced a maximum of 22 tons/h of steel tubing with outside diameters between 0.03 and 0.13 m;
the billets from which the tubing is made have diameters from 0.13 to 0.23 m and lengths from 0.25 to 0.87 m.

- A second line with a 5500-ton press extruded 75 billets per hour and produced a maximum of 57 tons/h of tubing with outside diameters between 0.04 and 0.24 m; in the case of this line, the billet diameters range from 0.2 to 0.4 m with lengths of 0.48 to 1.4 m.

Induction systems have been supplied for both lines for heating billets before piercing (expansion) and before the metal’s extrusion.

The piercing requires that the steels are heated to a temperature of approximately 1200°C. For the 2000-ton line, the three horizontal in-line multicoil induction heaters operate in parallel.

On the other hand, mixed heating is used in the 5500–metric ton line. First, a rotary hearth furnace preheats billets to approximately 850°C, while the final heating from approximately 850°C to 1200°C is carried out in three horizontal in-line induction heaters also operating in parallel. These three groups of heaters are generally made to work at a constant production rate but, in the event of any irregularity of the line, they will immediately provide a hold or standby mode of operation.

During the piercing operation, the billet cools down unequally and must be reheated before extrusion. This reheating from approximately 900°C to 1250°C takes place in two rows of vertical inductors in which each billet is individually reheated using a static heating mode. These inductors thus take into account an initially nonuniform temperature profile and enable the temperature of all the billets to be raised to the same level and with required uniformity for the extrusion process.

The 2000-ton line comprises seven 650-kW vertical reheating inductors, among which six operate continuously, with the seventh being held in reserve. In the case of the 5500-ton line, it comprises eight 1200-kW vertical inductors, among which seven inductors operate continuously, with the eighth being held in reserve.

6.3.1.3.1 Prepiercing Horizontal In-Line Induction Heaters

Each horizontal in-line induction heater (Figure 6.28) facilitates operating flexibility, including frequent changeovers, when it is required to provide the holding (standby) operational mode of the heater in the event of irregularities of the production line [606]. A computer controls and optimizes the heating.

The heating zone of each horizontal in-line heater is 7 m long and comprises five in-line induction coils aligned along a metallic chassis. Infrared pyrometers monitor the temperatures of critical zones.

In the case of the 2000-ton line, the billets are charged from pallets, and in the case of the 5500-ton line, a roller track carries the billets after their passage through the rotary hearth furnace. After stopping at one of the measuring stations, the billets are distributed among the three horizontal in-line induction heaters by means of transverse moving trolleys. After being delivered, the billets are subsequently moved into the appropriate heater.

The pusher that operates in small steps or fractional billet lengths is used to charge billets into the heater and ensure the required temperature uniformity along the billet length. The pusher is long enough to automatically empty the charged heater when required.

At the entrance to the inductors of the 5500-ton line, fed with billets preheated to 850°C, a small electric resistance holding furnace is located. This furnace maintains the
temperature of the billet until it is fully inserted into the first inductor by the step-by-step action of the pusher.

At the exit of each horizontal induction heater, there is also an electric resistance holding furnace to maintain the billet leading end temperature until its tail end has completely left the last coil. This furnace also enables the differences in the production rates between the press line and the heaters to be evened out.

Billets are taken out of the electric resistance furnace by a tongs extractor that pulls them through an automatic separating mechanism. Only one billet is drawn onto a transverse moving trolley serving all three horizontal heaters, to be made available to a press or be rejected. This acceptance or rejection decision is made by a pyrometer located in the discharge holding furnace.

A control system carries out the total control of the operation, including control of the pushers, extractor tongs, and trolleys, as well as the tracking of the billets. In the event of a delay at the press, the induction heater will automatically change over to a holding mode.

### 6.3.1.3.2 Pre-Extrusion Vertical Induction Billet Heaters

In order to feed the 2000-ton press, six vertical 650-kW coils plus a standby inductor reheat 22 tons of steel billets per hour (maximum production rate) from 900°C to 1250°C. These inductors are designed to handle billets ranging from 130 to 240 mm in diameter (Figure 6.29a). In order to maintain a reasonably high coil efficiency when heating billets with different diameters, extra coil sets with different coil I.D. are used.

In the case of the 5500-ton press, there are seven vertically arranged 1200-kW coils plus one standby coil that can reheat 57 tons of steel billets per hour from approximately 900°C to 1250°C. These inductors are designed to handle billets ranging in diameter from 200 to 420 mm using several coil sets. It is also possible to heat cold billets from 20°C to 1250°C at a lower production rate.

The inductors have a number of taps to adjust the length of the coil to that of the heated billet. Each vertical inductor has two pyrometers (Figure 6.29a).

The billet transfer, tipping, and charging mechanisms are located below the platform and operate as follows [606]:

- The billets to be reheated are brought to the vertical cells by means of a trolley conveyor (2000-ton line) or a roller track (5500-ton line); the billet is brought in front of the vacant inductor either by the stoppage of the trolley (2000-ton line) or by a retractable stop on the roller track (5500-ton line).
The billet is then transferred sideways by the tipping of the trolley platform (2000-ton line) or by a canted diverting arm inserted into the roller track (5500-ton line); the billet rolls off into an intermediate station and then onto a horizontal cradle; this cradle forms part of a rocking hanger, which pivots 90° and sets the billet vertically over a charging jack.

The charging jack is installed at the basement level and raises the billet vertically into the inductor; it moves through its full travel so that the lower end of the billet is always positioned at the same level in the inductor, while its upper end is in the zone where the taps are located. All the jacks operate with a nonflammable mixture. The heating operation is automatically started once the billet is completely charged. The process of IH is controlled as a function of the required energy and is readjusted as a function of the initial temperature and the transient temperature measured by pyrometers during the heating cycle. This approach ensures that all billets are heated to the required extrusion temperature.

When the heating cycle is completed, the programmable controller generates a signal that checks whether the press is available to accept the billet. If not, the inductor changes its heat mode over to hold mode.

Billet discharge occurs by the lowering of the jack followed by the 90° pivoting of the hanger, thus bringing the billet into a horizontal position on the cradle (Figure 6.29b). The cradle then tips and unloads the billet onto the trolley conveyor that takes it to the extrusion press.

Since the commissioning of the above-described system, novel designs have appeared quite regularly. One of the major challenges in the effort to provide a sufficiently uniform final temperature distribution before extrusion is associated with an inductor’s ability to compensate for a substantially nonuniform initial heat profile. For example, it is not unusual to have the following temperatures after the piercing (expansion) operation: I.D. = 1050°C–1100°C, O.D. = 900°C–950°C, temperature of billet ends = 780°C–840°C. This 3-D nonuniform temperature distribution before reheating is primarily affected by the following factors: specifics of press operation, types of lubrication, metal grade, and transportation time from the piercing (expansion) station to the induction reheat station. Figure 6.30 shows an example of temperature nonuniformities of the steel billet before reheating.
In some cases, the final temperature after induction reheat is required to be nearly uniform (Figure 6.31a), but in other cases, the I.D. temperature of discharged billets is intentionally kept slightly lower compared to the O.D. temperature (Figure 6.31b), and heat equalization takes place during the billet transportation to the press, which can take 15–30 s. In cases when there is considerable billet transportation time from induction reheater to extrusion press, it might be beneficial to have some heat surplus in the end areas. This is particularly important for thin-wall hollow billets because they experience a much greater cooling effect in the end zones compared to the billet’s middle area.

A pyrometer positioned at the coil entrance can be used to monitor the longitudinal surface temperature distribution of a billet that is being loaded into an inductor. This helps quantify the initial end underheating of the billet’s ends to develop an appropriate heating recipe.

Initially, a single-zone inductor design was used for heating large billets. In many cases, this was the most cost-effective approach that provided sufficient temperature uniformity at the end of the heating cycle. Later, a multizone design was developed to better address certain process requirements.

Banyard Ltd. (presently Inductotherm Heating & Welding Ltd., UK) was the first manufacturer of IH equipment to use the multizone control approach, which was originally developed for heating large aluminum billets (Figure 6.32). In multizone control, the induction coil consists of multiple sections (typically four to six sections depending on the length of the billet). Multizone LFi Banyard induction systems (produced by Inductotherm Heating & Welding Ltd.) can serve as a good example of advanced

![FIGURE 6.30](image1)

Examples of temperature nonuniformities of the steel billet before reheating.

![FIGURE 6.31](image2)

Typically, the final temperature after induction reheating is required to be uniform (a), but in other cases, the I.D. temperature of discharged billets is intentionally kept slightly lower compared to the O.D. temperature (b) and heat equalization takes place during the billet transportation to the press.
engraving of such systems. The power of each section can be individually controlled, providing greater flexibility.

Each approach (single-zone control vs. multizone control) has its own pros and cons, which are briefly analyzed below [559].

6.3.1.3.3  Pros for a Single-Zone Design versus the Multizone Concept

- Capital cost for a single-zone design is noticeably lower compared to a multizone design.
- Billet’s regular (middle) area is exposed to a homogeneous magnetic field and thus will be heated uniformly. Therefore, process control can be primarily focused on achieving the needed heat uniformity in the billet’s end zones. This simplifies monitoring.
- A single-zone control system allows for finer adjustment of coil overhang to accommodate various billet sizes. In modern inductor designs used in a single-zone arrangement, every second turn can be tapped to obtain a suitable coil overhang. Adjustability of coil overhang is approximately 40–50 mm. However, if required, it is even possible to tap every single turn, which further improves smoothness of the end effect control. In contrast, with a multizone system, the minimum length of each section that comprises an inductor is typically at least three times greater than 0.04 m, typically being 0.15 m or longer. This may result in coarser adjustment of the coil end effect with corresponding deviation in heat distribution.
- The longer active coil length used in a single-zone design is associated with an increased coil electrical efficiency compared to shorter sections of the multizone design.
- The single-layer coil design has been widely used in numerous IH systems since the early 1950s as a well-established technology. The multilayer design that is often used with multizone control is inevitably more complex (e.g., requiring more utility connections, etc.) and may result in reduced efficiency when heating materials with high–electrical resistivity steels, Ni-based superalloys, and titanium alloys, because it is associated with the well-known electromagnetic shielding effect of internal layers in respect to external layers, especially when using higher
frequencies. The shielding effect results in additional kilowatt losses. The shield-
ing effect of internal layers does not exist in a single-layer coil.

- The use of a single-layer inductor winding allows one to reduce the total number
  of turns and apply substantially wider copper turn cross sections, which can also
  help reduce total copper kilowatt losses.

- Fewer components involved in design and process control and monitoring. A sys-
  tem with more components typically has a higher failure rate. A single power
  supply will naturally have fewer components susceptible to failure, less required
  maintenance, and a generally less complicated system.

6.3.1.3.4 Pros for a Multizone Design versus the Single-Zone Concept

- The multizone design provides better capability to take into account potential
  billet-to-billet heat variability. This may serve as a comfort factor for some cus-
  tomers, allowing them to better compensate for severe initial heat nonuniformity.
  When there is a substantial axial temperature nonuniformity of incoming billets,
  the multizone design provides greater process control flexibility. In cases when
  the initial temperature of billet ends is drastically lower compared to the middle
  zone, this might be the most appropriate design.

- Flux concentrators and flux extenders positioned at the end zones frequently
  required with a single-zone design might not be needed with a multizone design.
  Therefore, there will be less energy wasted within the flux concentrator/flux
  extender (also referred to as “the mole”). Such devices often have a short life and
  considered to be sacrificial items.

- Large coil overhangs might be required in some cases when using a single-zone
  design, which could lead to additional kilowatt losses within the copper turns of
  the coil overhang regions.

- Four to six pyrometers are commonly required by the multizone design to provide
  more complete information about the billet thermal conditions, allowing the con-
  trol system to “act” on those data. This assumes that information received from
  pyrometers is sufficiently accurate regardless of the presence of heavy surface
  lubrication/glass coating on the billet’s surface, which may not have a uniform
  thickness.

- Temperature control utilizing only coil overhang (in case of a single-zone design)
  faces some limitations, namely, trying to balance the heat of the central zone and
  end zones.

- Multilayer coil designs may exhibit higher electrical efficiency when heating low-
  resistive metallic materials (e.g., Al, Cu, Ag, etc.).

- When heating very short billets, a single-zone system might face limitations
  related to a load-matching capability. The multizone design typically simplifies
  load matching.

On several occasions, we have referred to using magnetic flux concentrators and flux extend-
ers. It should be noted that these two terms do not represent the same electromagnetic device,
though their effect of EMF distribution could be very similar. Space does not permit a discus-
sion of the difference in physical performance between these devices. Refs. [622,623] provide a
description related to differences in magnetic flux concentrators versus flux extenders.
6.3.2 IH of Nonferrous Billets

IH of nonferrous billets (i.e., aluminum, copper, brass, magnesium, silver, titanium, Ni-based superalloys, etc.) comprises the same basic design approaches as the heating of carbon steel billets. For example, after exceeding the Curie temperature, carbon steel responds to IH in a very similar way to stainless steels.

In contrast to titanium, stainless steels and Ni-based superalloy billet heaters, the heating of copper, magnesium, and aluminum alloys requires special design considerations. The principal differences arise because such materials as Al, Mg, and Cu alloys are much better electrical and thermal conductors. For example, the electrical resistivity of copper is 38 times (at room temperature) to 15 times (at a temperature of 900°C [1652°F]) lower than that of stainless steel. At the same time, the thermal conductivity of copper is 15 to 20 times higher compared to stainless steel.

The lower value of resistivity \( \rho \) results in a smaller \( \delta \), making it possible to apply much lower frequencies and often even use a line frequency when heating billets made from low-resistive metals such as Al, Mg, Ag, and Cu without facing the danger of eddy current cancellation.

Because the low-frequency inductors require low “volts per turn” values, the use of multilayer coil designs might be attractive to simplify load matching of the coil to a power source.

While discussing IH of such metals as Cu, Ag, Mg, Al, and the like, it is important to mention that because the thermal conductivity of those metals is quite high, it is easier to obtain a uniform temperature distribution within the heated billet. Another feature when heating billets made from Al and Mg alloys deals with the fact that such metals are heated to much lower temperatures compared to steels.

Thanks to a high strength-to-weight ratio, the use of magnesium and its alloys has been increased in recent years. Special care should be taken when dealing with pure magnesium and some Mg alloys because of its hazards, explosiveness, and highly flammable nature when in powder, small particles, dust, chips, ribbon forms, and so on. Magnesium critical temperatures are as follows:

- Autoignition temperature is approximately 473°C (883°F).
- Melting point is 650°C (1202°F).
- When burning, its flame temperature could exceed 3100°C (5600°F).

When heating Mg alloys, target temperatures often exceed the autoignition temperature, and in some cases, it is even higher than the flash point temperature.

Bulk metal is not nearly as flammable or explosive. Of course, during the processing of magnesium billets and its handling, there might be some inevitable small particles and Mg dust accumulations, which would raise a concern regarding flammability/explosive hazards.

Burning magnesium reacts violently with water. Therefore, water cannot be used to extinguish magnesium fires; the hydrogen gas produced only intensifies the fire. Special fire extinguishers should be applied. Preventive measures should be used to eliminate the possibility of sparks occurring. When working with powdered pure magnesium or in cases of considerable Mg dust accumulation, safety glasses with welding eye protection must be available, because the bright white light produced by burning magnesium contains ultraviolet light that can damage the eyes. It must be assured that smoking is prohibited in the areas where there is a possibility of accumulation of pure magnesium powder,

This section concentrates on the discussion of aluminum billet heaters. Aluminum is typical of the family of low-resistive, high thermally conductive metallic materials, and therefore the majority of design features of aluminum billet heaters will be similar for IH of billets made from copper, brass, gold, silver, magnesium, and the like.

The first industrial inductor for heating of light metal billets is believed to have been built to fulfill the needs of the aluminum industry around 1950. The conventional single-layer solenoid coil design was used for heating aluminum billets.

As has been discussed earlier, low electrically resistive metals are known to have a low coil electrical efficiency. The power loss in any IH system includes losses in power supply, capacitors, and transmission; loss of power generated in the coil surroundings (i.e., tooling, rails, frames, cabinet, rolls, etc.); thermal losses from the billet’s surface; and actual losses in the coil copper windings. When heating nonmagnetic low-resistive metals such as Al, the power loss in the coil copper windings is usually greater than all other losses combined. Therefore, the ability to reduce losses in coil turns represents the main avenue toward improving the total efficiency of an aluminum billet heater.

An obvious attempt to decrease power losses in coil windings is to reduce coil resistance $R_{\text{coil}}$ that in a simplified way can be determined as follows: $R_{\text{coil}} = \rho_{\text{coil}} \cdot \frac{L}{A}$, where $\rho_{\text{coil}}$ is the electrical resistivity of the coil windings, $L$ is the length of current-carrying conductor, and $A$ is the area through which the current flows.

Generally speaking, $\rho_{\text{coil}}$ can be reduced using low-resistive metals. Unfortunately, there are only few options in using different metals for coil fabrication, as copper is one of the metals with the lowest electrical resistivity.

Theoretically speaking, the phenomenon of superconductivity can be used to drastically reduce the value of $\rho_{\text{coil}}$ and, therefore, significantly improve coil efficiency particularly when heating low-resistive metals. Studies show that because of the phenomenon of superconductivity when heating aluminum billets, the coil electrical efficiency can be increased from approximately 45%–55% to 80%–88%. Unfortunately, in order to create a condition for the existence of superconductivity, it is necessary to have extremely low subfreezing temperatures. In order to create such low temperatures, it is necessary to use liquid nitrogen for cooling coil turns instead of water. Such an approach would result in a significant increase of the capital cost of the equipment, leading to difficulty in providing a cost-effective, reliable, and robust system. Besides that, although the coil electrical efficiency can be noticeably improved when cooled with liquid nitrogen, the system total efficiency can still suffer because of poor efficiency of the cryogenic system.

Instead of trying to use different metals for coil fabrication, coil resistance can be minimized by diminishing the skin effect and increasing the area of current flow. For example, it is common practice to use Litz-wire technology in some transformer designs (see Sections 7.2.3 and 7.5.4) or when fabricating low-temperature pancake-type inductors.

Litz wire derives its name from the German word Litzendraht, meaning “woven wire” [395,615]. It consists of numerous individually insulated fine copper wires twisted or braided into a uniform pattern, so that each strand tends to take all possible positions in the cross section of the entire multistrand conductor. Litz wire eliminates the skin effect, leading to an increase in current-carrying area, reduced electrical resistance, and coil kilowatt losses. The main drawback for the wide utilization of the Litz-wire cables for coil fabrication is the difficulty of providing reliable cooling of Litz-wire cables that carry high currents.
In the late 1970s, the research and development of multilayer line frequency inductors was completed by the Capenhurst Research Center, UK. This technology has been exclusively licensed to Banyard Ltd. (presently Inductotherm Heating and Welding Technology, UK). During the intervening years, this technology was further refined. The study shows that properly designed multilayer coils could allow one to reduce coil copper losses by as much as 15%–20%, particularly in the case of single-phase coil designs [614].

High-efficiency multilayer coils for heating Al billets started to replace single-layer predecessors in the late 1970s and early 1980s. A popular type of induction billet heater at that time was based on using a multilayer multiturn coil connected to three single-phase transformers designed to provide the required kilovolt-ampere at the operating voltage of the coil. The transformers were provided with an offload tap switch to allow the secondary voltage and therefore the coil voltage to be varied. Because power density was voltage dependent, the taps allowed the induction heater to be set up to closely match the throughput of the extrusion press. In reality, the great majority of extruders set the heater to maximum and allowed it to go into the holding or standby stage while waiting for the next billet to be called by the press.

By setting each section of the three-phase inductor to a different voltage, it is possible to achieve a stepped temperature profile along the length of the billet, which approximates a rough taper.

The ability of IH to provide a tapered temperature profile along the billet’s length exhibited some benefits for heating aluminum billets before extrusion.

Generally speaking, there are two types of extrusion: cold extrusion and hot extrusion. IH is used for the heating of billets before hot extrusion, that is, the process of forcing a heated metal (e.g., aluminum, copper, steel, etc.) using a hydraulic force to flow through a shaped die opening. Hot extrusion is used to produce long, straight metal products of constant cross section, such as bars, solid and hollow sections, tubes, and wires that cannot be formed by cold extrusion [611]. The geometry of aluminum billets that feed to the extrusion press typically ranges from 0.1 to 0.5 m in diameter and up to 1.6 m in length.

There are two basic methods for hot extrusion: forward or direct extrusion and backward or indirect extrusion. In direct extrusion, the ram travels in the same direction as the extruded section and there is a relative movement between the billet and container. A typical metal flow pattern for direct extrusion is shown in Figure 6.33a. The temperature of the extruded material varies during the extrusion, depending on the process features including the type of extruded alloy, metal flow, ram speed, billet/container interface friction, and geometry of the extruded products. Temperature variation during hot extrusion could noticeably affect the structure and properties of the extruded product.

**FIGURE 6.33**
Metal flow during direct hot extrusion (a) and typical exit temperature variation of aluminum products during direct extrusion (b), assuming a uniform billet temperature before extrusion.
After the heated billet is loaded into the preheated container and the beginning of the extrusion, there will be a rise in the billet temperature (Figure 6.33b). There are two major sources for heat generation during extrusion:

- Heat generation attributed to internal shear and friction between the deforming metal and the container
- Heat generation attributed to plastic deformation

Studies show [612,613] that if ram speed is constant and the billet has been heated uniformly, the exit temperature of the extrudate rises rapidly, particularly during the initial stage of ram travel. It is beneficial to maintain the temperature of the extrudate, leaving the die area at a certain optimum level, a process called isothermal extrusion. This process provides several important benefits including an improvement of the quality of the extruded products, resulting in more consistent product shape, microstructure, and mechanical properties. In addition, the die experiences more consistent load during the entire extrusion cycle, leading to longer die life and potentially higher press production.

Isothermal extrusion can be achieved by

- Reducing the ram speed during extrusion (Figure 6.34a): This approach results in increased cost of the extrusion press owing to the necessity of having a sophisticated press control.
- Extruding at a constant ram speed a billet that has suitable thermal profile (the so-called taper-heated billet), resulting in an isothermal extrusion. The billet should have a hotter nose and cooler tail (Figure 6.34b). This can be achieved by either selective cooling of the uniformly heated billet (the so-called taper-cooled billet) using a water shower sprayed on the surface of the billet uniformly heated in the furnace or by a profiled IH that allows developing a required temperature gradient along its length.

Proper axial thermal gradient compensates for the heat generated during extrusion. According to another approach (the so-called hybrid approach), the billet can initially be preheated uniformly to a subfinal temperature that depends on the type of extruded alloy and extrusion practice (generally approximately 400°C [752°F]) using a gas furnace and then finally heated using a compact and lower-power taper heating inductor. The taper heating inductor can be located between the gas furnace and press.

![FIGURE 6.34](image_url)

Variation of extrusion speed, assuming uniform initial temperature (a) and taper heating for isothermal extrusion (b).
6.3.3 Hybrid Designs: Induction + Gas Furnace versus Gas Furnace + Induction

In some cases, hybrid designs consisting of a combination of an induction heater and a gas furnace are used. The two most typical scenarios of the hybrid designs are as follows: (1) IH followed by heating in gas furnaces, or (2) gas furnace is used first to provide steel preheating to temperatures of 800°C–900°C and then billets are heated to final temperature using induction heaters. Both approaches have their own advantages and can be used depending on the application specifics. Some of those features are briefly discussed below.

6.3.3.1 Induction Is Followed by Gas Furnace

When heating ferromagnetic materials (e.g., carbon steels), an electromagnetic induction provides rapid and highly electrically efficient heating at a temperature range up to a Curie point. Coil electrical efficiencies often exceed 80%–85%.

As has been discussed on numerous occasions earlier, upon exceeding Curie temperatures, much deeper heat generation takes place. For example, when applying line frequency, the heat sources can be generated within the surface layer of 70–75 mm (see Table 3.4), providing a significantly deeper heating effect that dramatically intensifies the heat flow toward internal regions of the workpiece and its core. After receiving the majority of the needed thermal energy in an induction system, a workpiece can be transferred to a gas furnace that solely relies on surface heating, providing a minor rise in billet’s mean temperature, primarily acting as a holding furnace for achieving required volumetric temperature uniformity.

Such an approach can particularly be beneficial when designing systems to heat irregularly shaped billets or components with various masses and complex cross sections including triangular, trapezoidal, rhomboid, hexagonal, parallelogram, polygonal, and others. The ability of IH to provide highly efficient and rapid (if required) bulk heating (as an induction booster) may be highly attractive since it allows a marked increase in production rate and dramatically reduces the scale formation owing to a significant reduction of the overall process time and most importantly the time when the steel surface is exposed to high temperatures.

6.3.3.2 Gas Furnace Is Followed by an Induction Heater

As an alternative design concept, the billets can be initially preheated in a gas furnace taking advantage of the lower cost of gas, which is, at the time of writing this book (2016), less expensive compared to the cost of electricity. After being preheated to temperatures of approximately 800°C–900°C, billets are transferred to an induction heater to be finally heated, benefiting from the deep heat generation capability of reaching the final target temperatures.

Beside the advantage of using lower cost of utility, there will be additional cost savings since the maintenance cost of the gas furnace will be dramatically reduced as a result of operating at much lower temperatures. This concept is also attractive when heating alloys that exhibit low toughness/high brittleness.

Reader’s Question: “We process copper alloy bars and billets in our factory. Gas furnaces have been used to heat billets made of C14500, C44300, C46400, C48500, C64200, and others. Billet/bar diameters are within the 200- to 240-mm range. The maximum temperature of our furnace is 860°C, which is sufficient for these jobs. However, we are expanding our business and processing grades such as C71500, C63000, and some other copper alloys that require temperatures of 950°C–1050°C. Could we use our gas furnace for billet preheating and then use a gantry system to move billets to an induction heater for final heating to take place?”
**Answer:** Yes, this approach will help you reduce capital costs because your new induction system will only require raising billet mean (average) temperature to less than 200°C. Depending on the necessary production rate and required temperature uniformity (surface to core and end to end), you may use a number of static induction heaters to reach the target temperatures. Keep in mind that if the lengths of your billets/bars vary noticeably, you will need to properly control electromagnetic end effects by applying adjustable turns, magnetic flux extenders, and flux concentrators. Considering the diameters of your billets, the use of low frequencies (50–120 Hz) will most likely be appropriate. Time of billet transportation after preheating in the gas furnace and final heating in the induction system should be kept to a minimum. Lengthy transportation times can disrupt the heat uniformity obtained in the gas furnace, requiring compensation by the induction heater and complicating system design.

The challenges with IH of copper alloys such as C71500, for example, are associated with their extremely low thermal conductivity [68–74]. In the case of C71500, alloy thermal conductivity is more than 14 times lower than the thermal conductivity of pure copper and more than 12 times lower than the C14500 alloy you are now processing. Because of the lack of thermal conduction, much lower surface-to-core heat transfer will occur, leading to a reduced heat equalization effect and increased thermal gradients. Thus, sufficient time is needed.

In addition, the electrical conductivity of C71500 is only 4.6% that of pure copper [68–74]. This increases current penetration depth and electrical efficiency but reduces the required power consumption: This means that the maximum required power might be deceiving for a similar-sized billet and production rate for a different copper alloy such as C14500. The electrical resistivity of copper alloy C71500 is only approximately 54% of austenitic stainless steel and its thermal conductivity is approximately 1.6 times that of nonferrous stainless steel. In other words, both electromagnetically and thermally speaking, copper alloy C71500 responds to IH more like stainless steel than copper.

The subtleties of new copper alloys must be addressed when designing an induction heater to be positioned after a gas furnace.

### 6.4 Bar/Billet/Rod End Heating

Although many of the bars, billets, or rods being manufactured today lend themselves to processes in which entire workpieces are heated and fed into a forming machine, in some cases, it is required to hot form only selected region(s) of the workpiece, for example, its end(s). Some examples of these types of parts are “sucker rods” for oil country goods or various structural linkages in which an eye or a thread may be added to one or both ends of the bar (Figure 2.22).

Placing the region of the workpiece that needs to be heated (e.g., the end of the bar) in an induction coil and heating it for a specified amount of time generally accomplish selective heating. Some end heating applications require specific temperature profiles along the length of the workpiece, including sharp or gradual cutoff of the heat; others prefer a gradual transition zone.

In its simplest form, a static heat mode with manual loading can be used to heat the end of the bar by placing the workpiece into the proper position within a coil, allowing appropriate power at a selected frequency to do its work and ensuring the required production.
Multiple bar ends can be heated in a single-turn or multiturn oval coil (Figures 6.35a and 6.36), as well as in a channel-type inductor (also referred to as a slot or skid coil, Figures 6.35b and 2.22b), or utilizing multinest arrangements with two, three, four, or more individual conventional solenoid coils (Figures 6.37 and 6.38). Multiple coils are used to increase the production rate.

When using channel coils, care must be taken to insert the workpieces into the coil to an appropriate depth and hold them at that relative location while bars travel through. By the time a bar reaches its final heating position inside the coil, it will obtain the required thermal condition [405].

Electrical efficiency usually suffers when using channel-type coils compared to a conventional solenoid type, and a further detriment is the potential for uneven heating along the bar perimeter. Because of the electromagnetic proximity effect, more intense heating occurs in the areas of the bars closest to the coil (Figure 4.155). This phenomenon may result in unacceptable temperature nonuniformity. Attempts should be made to avoid an overheating of butt end of the bars at the final heating position. Various know-hows have been developed in industry to minimize butt end temperature surplus.

Low heating intensity and a subsequent increase of the heat time as attempts to improve circumferential heat uniformity will promote a heat transfer toward the colder bar end owing to thermal conduction, which can lead to several undesirable phenomena. First, an increase in the heat time might lead to the formation of an unacceptable amount of metal loss as a result of scale. Besides that, an intense axial heat transfer provides undesirable

![FIGURE 6.35](image1)

(a) Oval coil bar end heater (a) and channel coil bar end heater (b).

![FIGURE 6.36](image2)

High-production oval coil for heating ends of steel billets. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
heating of the cold end, which increases energy consumption and is associated with the waste of energy.

The oval coil is a more efficient and reduces the risk of bar end overheating than the channel coil. In the case of the oval coil design (Figure 6.36), bars are loaded into a magazine from which they are pushed, one at a time, into the upper end of an inclined oval coil. They roll down as previous bars are removed.

Oval- and channel-type inductors are the most suitable options employing automated handling when high production rates are needed. It should be mentioned, however, that these types of coils are not very well suited to process bars when long heated lengths are required.

It is important when applying the oval or channel coil designs to pitch the heated workpieces as close together as possible; however, having a sufficiently small pitch, the mechanical aspects of the machine may be constrained. While in process, it is also important to
Induction Mass Heating

keep the heated parts centered within the coil; otherwise, an additional uneven heating problem might occur because of the proximity effect.

The choice of a particular arrangement of induction end heater depends on the application and the customer's preference. However, because the highest efficiency and the best temperature uniformity are obtained with a solenoid coil, every effort should be made to use it wherever possible.

In addition to the variety of coil arrangements, the loading/unloading operation can be fully automated, semiautomated, or manual; the choice depends on the required production rate and the cost [562,609].

For low and moderate outputs, workpieces may be indexed through several solenoid coils. At the same time, as the production rate increases, the number of coils rises, and time lost in the index process becomes progressively more significant. The time when bars are not within the coils during indexing leads to extra heat losses and subsequently requires a higher installed power compared to the case where the heated workpieces remain within the coil. On the other hand, the time when heated bars are outside the coil during indexing might still be beneficial to some degree in providing the required surface-to-core heat uniformity and avoiding surface overheating.

Manual or semiautomated designs where the operator simply removes the hottest bar and replaces it with a cold bar is the least expensive approach. Figure 6.37 shows two typical semiautomatic loading/unloading methods using multiple solenoid coil arrangements. Figure 6.38a shows a 700-kW/3-kHz 10-station semiautomatic bar end heater, producing 400 bar ends per hour heated to 1232°C (2250°F).

Although there are a variety of end heating design arrangements and alternatives, the basic principles in obtaining the required temperature profile within the bar end are quite similar. Some process features of the induction bar end heater have been discussed in Section 3.1.7.1 (Figures 3.35 and 3.39 through 3.43).

An important feature that defines the coil length is the fact that in zone “b” (Figure 3.35), which is often called the transition zone, there is a significant temperature gradient along the length of the workpiece. As a result, heat is conducted from the high-temperature region of the bar toward its cold area. This thermal sink phenomenon is more pronounced when heating metals with high thermal conductivity (e.g., Al, Cu, etc.). The proper choice of coil geometry, power density, and frequency will allow one to compensate for this cooling effect and obtain the required uniform temperature profile for the bar with a minimum transition zone.

A short cycle time, high power density, small coil-to-workpiece radial gap, and high frequency help make this zone shorter. Application of external magnetic flux concentrators also allows shortening the transition zone.

Heat flow occurring as a result of the heat sink affects the amount of mass being heated and energy consumption. Over the years, some recommendations have been made for providing a rough estimate of the heat sink effect. An accurate assessment of the needed power, temperature distribution within the bar ends, and required coil design parameters can be conducted using numerical analysis (Figures 3.39 and 3.40).

Obtaining the required temperature uniformity along the length of the bar by choosing a proper coil overhang is only one of the possible design approaches to control end effects. Figure 4.153 shows a variety of end heating design concepts that help provide uniform heating using a multiturn solenoid coil. One example of a commercial low-cost induction bar end heaters is shown in Figure 2.22.

Figure 6.39 shows Radyne’s (presently Inductotherm Heating and Welding Technology, Ltd., UK) unique award-winning bar end heating installation supplied to an automotive plant in the United States to manufacture 600 flanged axles per hour. The robots
sequentially load and unload the 16 induction coils. Robots 1 and 2 automatically sequentially load bars into solenoid coils and robots 3 and 4 unload heated bars and place them in an “accept” or “reject” position. The 2000-kW/3-kHz installation heats bars up to 0.05 m diameter and 1 m long with heated lengths up to 0.38 m for upset forging. The final temperature is 1260°C (2300°F). Since the first equipment was commissioned, the customer has experienced higher efficiency over the previous heating system, very accurate and repeatable temperature profiles, longer die life, improved quality, and high reliability.

6.5 Billet/Slug Heating for Semisolid Processing

Semisolid metal (SSM) casting was originally developed at MIT in the 1970s. SSM casting has several advantages compared to casting in the fully liquid stage. This includes a lower level of product porosity and higher flow viscosity during casting [557,558,560,561,569]. The former provides predominantly laminar flow during casting.
This results in higher quality of cast products by prevention of the entrapment of gas. Figure 6.40 shows samples produced by semisolid casting of aluminum alloys. The SSM casting requires preheating a metal slug to obtain a semisolid condition (partially liquid and partially solid). Figure 6.41a shows a sliced aluminum alloy slug in a semisolid state.

6.5.1 Nature of Semisolid Processing and Basic Phenomena

Several metallic alloys have been used for SSM casting, including copper, magnesium, nickel, and some others. However, most of the commercial success in SSM forming centers around aluminum alloys, particularly alloys 356 and 357. In aluminum alloys, a typical liquid fraction of approximately 0.5 (50%) is considered to be optimum.

It is imperative to obtain a uniform temperature throughout the slug with uniform distribution of the liquid fraction. The need for a uniform liquid fraction distribution is demonstrated by the rheology curve shown in Figure 6.41b [558]. At a liquid fraction of approximately 0.5, the rheology of the semisolid alloy changes rapidly with only a small change in liquid fraction. Thus, if the semisolid slug has an end-to-end or surface-to-core variation in the liquid fraction, this will have a negative impact on the casting behavior as well as on the quality of the castings produced. If the liquid fraction exceeds its optimal value, then a significant amount of liquid metal might drip out of the slug, leading to unnecessary metal loss. In addition, an excessive amount of the liquid fraction can introduce some slug handling problems.

Practice shows that the best results of semisolid casting of aluminum alloys are obtained when the ratio of slug length to slug diameter is 1:2 to 1:3. An attempt to cast long slugs (i.e., with a ratio of 1:6) may result in a segregation problem.

IH has been identified as the process that meets criteria for preheating SSM materials. There are two types of induction coil arrangements: vertical and horizontal (Figure 6.42). There are no principal differences between these two approaches from electromagnetic and heat transfer perspectives.

**FIGURE 6.41**
Sliced aluminum alloy slug in semisolid stage (a) and an example (b) of a rheology curve (Al: 4.5%, Cu: 1.5% Mg, ε = 0.03 K s–1). (From S. Midson, Semi-solid castings of aluminum alloys: A status report, *Modern Castings*, February, 41, 1997.)
Figure 6.42b shows an example of a horizontal coil arrangement. As one can see, the system design is similar to that of a conventional billet heater described in previous sections. The only difference lies with the use of “boats” for carrying the semisolid billets.

The vertical approach is associated with equipment compactness and significantly lower capital cost. In a vertical coil arrangement (Figure 6.43), slugs are placed on ceramic pedestals and heated to the semisolid casting temperature. Once semisolid, the slugs are transferred to the shot sleeve of a real-time controlled horizontal die casting machine and cast in reusable steel dies.

As mentioned earlier, the quality of semisolid castings is greatly affected by the ability to achieve temperature uniformity within the slug. Depending on the alloys, the required temperatures for aluminum slugs are typically in the range of 575°C to 595°C with a required uniformity of ±3°C–4°C.

IH for semisolid forming has specific requirements for frequency selection. The choice of frequency here is defined not only by the required temperature profile in the slug but
also by minimizing EMFs (Lorenz force). Besides a radial component of force, heated slugs experience axial forces that are directed out of the coil. Excessive EMFs may result in the uncontrollable removal of liquid metal and an excessive slug shape distortion. Therefore, special attention should be paid to the minimization of these forces.

Even under normal heating conditions, an occurrence of the electromagnetic end effect is markedly different at various stages of the heating cycle. This is attributed not only to the change of electrical resistivity of the aluminum but also to several unique features of the SSM IH, including the “elephant foot” effect, slug tilting (sagging), and surface erosion phenomena. Figures 6.44 through 6.46 show shape distortion of aluminum slugs that reached a semisolid condition in vertical and horizontal coil designs.

6.5.2 Shortcomings of Mathematical Modeling of IH for Semisolid Casting

Mathematical modeling is a major factor in the successful design of an IH system. Unfortunately, the features of IH for semisolid forming is associated with several challenges in applying practically all existing commercially available software. The presence of the elephant foot phenomenon (Figure 6.44a) is an illustration that the slug has obtained a semisolid condition. As a result of this phenomenon, the coil-to-slug radial air gap will not be the same along the coil length/height at different stages of heating. Variation of the air gap changes the electromagnetic coupling. The power density distribution along the slug length/height will be different compared to the distribution within an “ideal” cylindrical body.

In addition to the elephant foot phenomenon, the slug tilting effect and surface erosion of certain surface areas (i.e., at the top of the slug) can make the situation even more complex. Because of tilting (Figure 6.44b), certain slug areas will have better electromagnetic coupling with the inductor than the areas located on the opposite side of the slug. Somewhat similar to positive feedback, the areas with better coupling will have more intense heating (owing to the proximity effect), resulting in more intense tilting.

Because of surface erosion at the top of the slug and the elephant foot phenomenon at its bottom, the length of the eddy current paths at the top, bottom, and central areas of the slug will be different. This will result in different resistance to eddy current flow in different surface areas of the slug and, therefore, in a different amount of Joule losses that appear within different regions of the slug. In other words, regardless of the fact that the entire slug is made from the same alloy, from an electromagnetic perspective, the slug will be seen by the magnetic field as a number of disks made from metals with different

![Figure 6.44](https://example.com/figure6_44.png)

"Elephant foot" phenomenon (a) and "slug tilting" effect (b) using vertical coil arrangements and computer graphics of magnetic vector potential distribution (c).
geometries and electrical conductivities. The elephant foot phenomenon, tilting effect, and surface erosion take place in both horizontal and vertical coil arrangements.

It is very important to remember that any computational analysis can at best produce only results that are derived from initial modeling assumptions. Even a cursory look at a computer-simulated magnetic field distribution (Figure 6.44c) reveals the danger in underestimating the slug’s shape distortion during the heating cycle, its impact on a redistribution of electromagnetic field, and using oversimplified assumptions such as considering a slug’s geometry as being a “perfect” cylinder. This assumption was valid in conventional IH before forging or extrusion; however, in SSM, such a hypothesis can lead to an incorrect mathematical model that will not be able to provide the required accuracy. In order to adequately simulate an IH of SSM, the computational model should couple electromagnetic, heat transfer, phase transformation, and metal flow phenomena, allowing one to take into consideration the dynamics of the shape distortion of the slug during the heating cycle. The development of software that will be able to take all four interrelated phenomena into account is a very complex task even for modern computers. Therefore, the recommendations obtained from conventionally coupled electromagnetic heat transfer software should be applied only for cases where elephant foot, slug tilting, surface corrosion phenomena, and other effects are not pronounced (as is sometimes the case with small slugs).

Another factor that affects the accuracy of any computer modeling is the availability of reliable material property data. There are a number of handbooks available providing electrothermal physical properties at elevated temperatures. Unfortunately, such information for SSM is very limited. In some instances, SSM property data exist, but due to measurement complexity and cost to conduct such a measurement, the accuracy of those data, especially in the most critical stages such as the spheroidization stage, is quite questionable.
Therefore, the results of SSM modeling using only the electromagnetic–heat transfer coupling approach should be considered only as a ballpark estimation.

### 6.5.3 Technological Aspects of Commercial IH Systems for SSM Forming

One of the traditional IH machines for heating aluminum alloy slugs is shown in Figure 6.43. It is a compact high-production carousel-style induction heater powered by a 350-kW/1-kHz power supply and comprises 24 pedestals and 18 induction coils. The cold slugs are loaded onto ceramic pedestals and indexed to the first induction coil. The coils are lowered around the slugs and the power is applied. After a preset time, the current is turned off and the coils are raised. The pedestals are then indexed forward by one position, the coils are lowered, and the process is repeated. In this manner, the slugs index from coil to coil until, at the final heating position, target thermal conditions and liquid fraction of the slugs are obtained.

This induction heater has been designed to match the throughput of the horizontal casting machine, which typically operates at a cycle rate of between 30 and 90 s, depending on the size of the castings and number of cavities being cast. This style of heater can heat aluminum slugs up to 5 kg (12 lb) in weight at this rate.

Because all the coils are connected in series (Figure 6.47a), two different designs of coils are used to provide the optimum heat cycle: intense heating and soaking. The intense heating coils (the so-called power coils) have a greater number of turns and are used to rapidly heat the slugs to the solidus temperature. The soaking coils have fewer turns (“holding coils”) and therefore finally heat the slugs, slowly providing gentle quasi-isothermal holding. This ensures that sufficient time is provided for the heat equalization, ensuring a sufficiently uniform temperature distribution and complete homogenization and spheroidization of the alpha-aluminum particles from the equiaxed dendrites found in the electromagnetically stirred SSM feed material [558].

A multicoil design allows one to properly handle electromagnetic end effects while the slug progresses from one heat position to another.

Typical recommended heating times for slugs with diameters of 76 mm (3 in.), 90 mm (3.5 in.), and 100 mm (4 in.) are listed in Table 6.9.

The induction heater in Figure 6.43 also utilizes an automated unit for cleaning any debris remaining on the pedestal once the semisolid slugs have been removed. Debris can

![FIGURE 6.47](image_url)

*The use of a single- or multipower supply approach for heating SSM slugs can be applied in both vertical and horizontal coil arrangements. (a) Series connection of coils powered from one power supply. (b) Each coil is powered from an individual power source.*
include drips or small pieces that were knocked off the semisolid slug during heating or pickup. This ensures that the pedestal is clean once it returns to the slug loading position, such that the cold slug will sit squarely on the pedestal. Devices such as the pedestal-cleaning device are important to ensure problem-free operation of the induction heater in a fully automated SSM casting cell.

The proper handling of electromagnetic end effects results in a sufficiently uniform top-to-bottom temperature profile with minimal appearance of the elephant foot effect and surface erosion. In contrast, incorrect handling of end effects can lead to a situation where the end of the slug that has the largest coil overhang would have a significantly higher temperature and liquid fraction compared to optimal, whereas the rest of the slug might not have any liquid fraction at all.

In Ref. [562], one can find a description of the physics of the impact of the coil overhang on the slug’s top-to-bottom temperature uniformity. These results indicate that it is very important to control the electromagnetic end effects in order to obtain the needed heat uniformity and liquid fraction and avoid tilting.

Different applications call for different design approaches. Some machines utilize one power supply that feeds all coils connected in series (Figure 6.47a). This approach allows one to significantly reduce capital cost. As an alternative, Figure 6.47b shows another approach where each coil is powered from an individual power source. Therefore, each coil is individually tailored to the required heating condition. This approach has an obvious advantage in regard to process controllability, allowing (if required) slugs to be held within the inductor for a relatively long time. This feature is important in cases when the casting machines experience downtime.

The obvious drawback of this approach is a significantly higher capital cost, and under certain conditions, this approach may actually exhibit lower controllability in controlling electromagnetic end effects at different heating stages compared to the approach shown in Figure 6.47a.

<table>
<thead>
<tr>
<th>Slug Diameter (in.)</th>
<th>Optimum Heating Times (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>9</td>
</tr>
<tr>
<td>3.5</td>
<td>12</td>
</tr>
<tr>
<td>4.0</td>
<td>16</td>
</tr>
</tbody>
</table>


### 6.6 Intricacies of Induction Wire/Cable/Rope Heating

#### 6.6.1 Specifics of Design Criteria and Coil Arrangements

There are several methods to heat wires, cables, and ropes including gas furnaces, electrical resistance heaters, infrared furnaces, electric ovens, molten lead baths, salt baths, and induction heaters.
Growing environmental concerns for global warming in combination with the requirement of increasing production with reduced equipment footprint have resulted in heating by induction becoming the dominant method for heating of both ferrous and nonferrous wire-like workpieces [564]. Thanks to induction, the use of molten lead and salt baths for heating of wire products has practically been eliminated. Other advantages of IH include instant heat generation and the possibility of incorporating a protective atmosphere. Quick response and the ability to provide an instantaneous change in the process operating parameters to accommodate the required temperature of the wire/cable being processed at speeds up to 5 m/s are also noticeable benefits of compact induction systems compared to fluidized beds, infrared heaters, and gas furnaces. The physical nature of wire processing makes it beneficial to use continuous-feed material handling.

The extensive use of electromagnetic induction for heating wire and cable products in a variety of applications has led to the development of a wide range of process concepts. As one can see from Figure 6.48, in addition to traditional applications (e.g., hardening, tempering, stress relieving, etc.), there are other highly efficient applications including but not limited to wire/cable heating before encapsulation, tire cord diffusion, subcritical annealing and recrystallization (see Section 2.1.4), quench annealing in manufacturing springs, wire heating before metallic or organic coating, and others.

Heating before encapsulation is typically applied to aluminum alloy wires. The wire is preheated as it leaves the payoff roll and the induction coil is positioned on the catenary of the wire line. The wire passes through the inductor where it is heated to approximately 120°C and then immediately transferred to the encapsulation process where the PVC flows evenly over the wire.

In drawing wires made of austenitic stainless steel, an excessive work hardening might take place making the wire to be too hard to continue to be drawable. Recrystallization is required in order to make a wire sufficiently soft, improving its drawing capability. This can be achieved by heating austenitic stainless-steel wire to temperatures of the 1050°C range followed by rapid cooling to avoid precipitation of carbides, which could worsen corrosion resistance properties. Direct water quenching cannot be applied here. Instead,
specially designed water-cooled tubes/jackets filled with protective gas are used during initial and intermediate cooling stages.

Tire cord diffusion may require simultaneous heating of 10 to 24 wires running in parallel and being heated to a temperature of 600°C to melt the surface alloy coatings (e.g., zinc alloys) that diffuse into the base steel wire to provide a barrier for rust and corrosion. Wire diameters typically range from 0.8 to 2 mm, and the process is described in Refs. [570,571].

Besides the case study discussed above, there are other applications where it is required to heat multiple wires running in parallel or processing several cables consisting of many wires and strands or wire bundles (Figures 6.49 and 6.50). The great majority of induction wire/cable heating applications apply solenoid-type multiturn coils (cylindrical or rectangular shape) with coil turns connected electrically in series or in parallel.

In most single wire processing applications with wire diameters less than 3 mm, the entire wire is usually heated through and the criterion of obtaining surface-to-core temperature uniformity is not an issue unless extremely short heat times are used.

Therefore, when heating multiple wires running in parallel or multistrand cables, the criterion of providing an equal temperature in all wires regardless of their position inside the inductor becomes critical. The former is a result of the fact that external and internal wires of the cable may be heated differently because of the electromagnetic proximity effect of the external and internal wires.

Several process features and physical phenomena distinguish IH of multiple wires and cables from conventional IH of solid cylinders, bars, and single wire heating.

**FIGURE 6.49**
Sketch of transverse section of multiwire cable IH system. (From V. Rudnev et. al, Intricacies of induction wire/cable heating, *Proceedings of the 71st Wire & Cable Symposium*, Atlanta, May, 2001.)

**FIGURE 6.50**
Sketch of transverse section of a multistrand cable IH system.
6.6.2 Energy Efficiency

6.6.2.1 Frequency Selection

Coil electrical efficiency is a complex function of several design parameters including the gap between coil I.D. and wire O.D., properties of heated metal, coil length, number of wires/strands, and frequency, with the former being the most prominent.

In the case of IH of a single wire, there will be higher coil efficiency when the applied frequency corresponds to a ratio of wire O.D. to current penetration depth ($\delta$) greater than four (wire O.D./$\delta > 4$; see Figure 6.19). The use of very high frequencies (frequency $> F_2$) may even decrease the electrical efficiency owing to higher transmission loss [564].

If the chosen frequency results in a wire O.D.-to-$\delta$ ratio of less than 3.2 (O.D./$\delta < 3.2$), the coil electrical efficiency will dramatically decrease. This is attributed to the cancellation of induced eddy currents circulating in the opposite sides of the wire.

In the case of heating multiple wires or multistrand cables, efficient heating can be achieved using lower frequencies or smaller-sized wires compared to the heating of a single wire. Analysis of Figure 6.51a shows that efficiency may increase with the number of wires/strands heated in the same coil (assuming relatively tight positioning of wires). In some cases, it is possible to gain an improvement in coil electrical efficiency that can approach 20% compared to the heating of a single wire.

Since the capital cost of a power supply usually decreases with a frequency reduction, the ability to use lower-frequency inverters can result in considerable cost savings for the user.

As shown in Figure 6.51a, the minimum frequency for efficient heating of multiple wires (frequency $F_3$) is shifted toward the use of lower frequencies compared to heating of a single wire (frequency $F_1$).

6.6.2.2 Ferrous and Nonferrous Wires

As discussed earlier, metals with high electrical resistivities are heated with higher coil efficiency than metals with low $\rho$ (assuming that there is no current cancellation).

![Figure 6.51](image-url)

(a) Coil efficiency of a multiwire cable induction heater versus frequency, where $N$ is the number of heated wires in a single coil. (b) Coil electrical efficiency versus frequency when heating tubes and pipes. (From V. Rudnev, D. Loveless, J. LaMonte et al., A balanced approach to induction tube and pipe heating, Industrial Heating, June, 1998, pp. 53–57.)
In the IH of magnetic wires, several unique aspects are encountered compared to non-magnetic ones. In contrast to bar/billet heating when heating magnetic wires/cables instead of three stages of the heating cycle, practically speaking, there are only two stages (magnetic and nonmagnetic).

At the first stage, the wire is magnetic, $\delta$ is small, the skin effect is pronounced, and coil efficiency is quite high. At the beginning of the heating cycle, the $\delta$ into the carbon steel wire will start to increase slightly because of the increase in $\rho$ with temperature. With a further rise of temperature, $\mu_r$ starts to decline, resulting in a marked increase of $\delta$ (Figure 3.14a). Thus, the first stage exists as long as the wire temperature is below the Curie point.

An excessively high increase in $\delta$ may lead to the eddy current cancellation within each single wire and, as a result, to a drastic reduction of the coil efficiency. In cases such as this, the application of a dual-frequency design concept can be beneficial (Figure 4.71). This concept makes use of low frequency in the initial heating stage, when the steel retains its magnetic properties. In the final stage, when the wire becomes nonmagnetic, it is more efficient to use a higher frequency.

The case study shown in Figure 4.71 emphasizes the importance of avoiding current cancellation when choosing an operating frequency. It is often required that the single wire induction heater be able to heat a variety of wire sizes to different target temperatures using a single frequency. It is imperative to choose a frequency, which would guarantee that, for any combination of wire sizes, materials, and final temperatures, severe current cancellation would not occur. It is wise to remember that while calculating the $\delta$, the values of $\rho$ and $\mu_r$ should correspond to their values at the highest temperature that expected to appear during the heating.

In some cases, it makes economical sense to choose the frequency based on the so-called big runners (wire sizes that represent the highest production). If there is an insignificant difference in the sizes of the big runners and smaller wires, then, in order to minimize the capital cost of the system, the choice of frequency can be determined by maximizing coil efficiency when heating the big runners with an accepted efficiency reduction while processing the smaller sizes.

Nonferrous wires/cable/ropes such as aluminum, copper, tungsten, brass, and so on can also be successfully heated using electromagnetic induction. However, coil efficiency when heating nonferrous wires and particularly those made of low-resistance materials is noticeably lower compared to heating magnetic alloys.

### 6.6.2.3 System Geometry Factor

The geometry of the induction system has a distinct effect on $\eta_{el}$. Similar to bar heating, the gap between the inside diameter of the coil (coil I.D.) and the surface of the wire/cable plays an important role in determining the coil electrical efficiency. Smaller air gaps result in better coil-to-wire electromagnetic coupling and thus greater coil fill factor, leading to higher efficiencies. At the same time, the minimum value of the coil-to-wire air gap is dependent on the ability to safely process all the required wire/cable sizes. Wire tension, diameter, the method of wire reel joining, and some other factors relate to the stability of the wire safely processing through the induction line.

The coil length is another factor that has a marked effect on $\eta_{el}$ and, therefore, on required power. Long and tightly wound coils are more efficient when heating both ferrous and, particularly, nonferrous wires compared to short and sparsely wound coils.
For nonferrous wires, it is recommended to have a coil length at least five times the coil inside diameter. If the coil length is less than three times the coil I.D., then the efficiency reduction can be quite substantial because of a nonhomogeneous magnetic field. For electromagnetically short coils, the use of magnetic flux concentrators (i.e., laminations or metal powder-based materials) may noticeably improve the efficiency, particularly when heating nonferrous wires.

If the coil length is five times longer than the coil I.D., then a further increase in its length will not provide any significant improvement in $\eta_{el}$. The former statement might not hold true when heating ferrous wires below the Curie temperature. In cases such as this, an increase in coil length results in a reduction of magnetic field intensity and, therefore, in an increase of the $\mu_r$. A gain in magnetic properties owing to a reduction of magnetic field intensity may lead to a coil efficiency increase. In addition, it makes the skin effect more pronounced by reducing the $\delta$ and allowing the use of lower frequencies compared to a short coil without sacrificing electrical efficiency.

### 6.6.3 Commercial Aspects of Induction Wire, Cable, and Rope Heaters

Because the response of an induction heater to changes in process parameters is practically instantaneous, the ability to provide consistent heating with smooth transitions (if required) creates a special requirement for the control system. Typically, one of two control methods is applied in induction wire heating systems.

- A closed-loop control system with feedback from an output temperature sensor or a line speed meter. Wire speed is detected to verify the throughput and to set the control algorithm for the process.
- An open-loop system utilizing feed-forward controllers. These controllers compute line speed and the required coil power based on the material, wire size, its production rate, and target temperature.

The ability to control individual wire speed when heating multiple side-by-side processed wires running in parallel allows the user to heat different wire sizes to various temperatures within the same coil (Figure 6.49). Depending on process-specific requirements, kind of metal, required tensile strength, and customer preference, a PLC or PC can be used to compute the required coil power and wire speed. The aspects of process control and monitoring are discussed in Section 6.7.

As an example, Figure 6.52 shows a typical in-line induction heater with a thermostatically controlled holding chamber with the ability to heat 18 wires (side by side running in parallel) in a hydrogen/nitrogen protective atmosphere [564].

Infrared pyrometers are used for temperature measurement and verification; however, the accuracy of temperature readings is affected by the ability to accurately focus the sensing head on the wire. Therefore, there is a potential problem in accurately focusing a pyrometer on the thin wire surface. Sometimes, because of process features, a wire cannot remain in a stable position and could, to some degree, move “up–down” and “left–right.” Therefore, there is a danger that the wire could move out of view of the temperature sensor, resulting in compromised readings and a false signal.

All these reveal that closed-loop control systems have not been as widely used for wire heating applications as open-loop systems with a controller.
6.7 Tube and Pipe Heating

6.7.1 Specifics of IH of Tubular Products

The extensive use of tubing in thousands of products being manufactured today demands a wide range of process concepts [1,565]. For example, in automotive manufacturing alone, new applications for tubing are being advanced at an expanding rate. From small- and medium-sized tubular parts such as stabilizer bars to intrusion and structural beams, steering columns, and shock absorbers, the list continues to grow. On the other hand, oil and gas lines with their high-pressure requirements represent another specific area of large-sized tubular products where heating by induction has proven to be effective. Figure 6.53 shows a portion of a variety of tube and pipe applications where IH can be used very effectively.

In order to better suit a particular heating requirement, a variety of coil arrangements and frequency/power selection are used. The design of some tube/pipe inductors has been adapted from heat-treating applications; others are quite similar to designs used in bar/billet heating. Although there are many similarities, there are several process features that distinguish IH of tubular products from heating solid cylinders. The specifics of maximizing coil efficiency represent one of these features.

The coil efficiency of an induction tube/pipe heater is a complex function of several parameters including the ratio of coil I.D. to tube O.D., metal properties, coil length, tube wall thickness, and frequency, with the last one being the most critical factor. As can be seen in Figure 6.19, in the case of IH of a solid cylinder, there will be high coil efficiency when the applied frequency corresponds to O.D./δ > 4. If the chosen frequency results in O.D./δ < 3.2 (frequency less then F1, Figure 6.19), the coil efficiency will dramatically decrease as a result of eddy current cancellation.

Figure 6.51b shows that there is a difference in the optimal frequency for IH of tubular workpieces as compared to solid cylinders. In tube and pipe heating, the frequency, which corresponds to maximum coil efficiency, is shifted toward lower frequencies (frequencies are between F4 and F2 for tubes instead of F1 to F2 for solid cylinders). The frequency
Induction Mass Heating

Induction Mass Heating

appropriate for heating hollow cylinders typically provides larger \( \delta \) than the tube wall thickness (except for heating of tubes with electromagnetically small diameters). This condition can result in a noticeable increase in coil efficiency. In some applications, it is possible to gain an improvement in electrical efficiency of 10% to 16% and even higher.

The total gain in efficiency when applying a lower frequency is not only derived from improvements in coil electrical efficiency but also the result of lower bus bar losses and shorter heat times. Another benefit of using lower frequencies deals with improved overall system cost-effectiveness, as, typically, the cost of lower-frequency power supplies is lower than that of higher frequency.

Computer modeling helps select the optimum frequency for a particular application. At the same time, in order to obtain a quick rough estimate of the most appropriate frequency, several simplified formulas are in use in the industry. For example, in the case of electromagnetically long solenoid-type inductors, some formulas are shown below [572]:

\[
F = 34.6 \frac{\rho}{A_m h} \quad (\text{Hz}),
\]

where
\( \rho = \text{electrical resistivity of heated metal (} \mu \Omega \cdot \text{in.} \)\)
\( A_m = \text{average diameter}; A_m = (\text{Tube O.D.} - h) \) (in)
\( h = \text{wall thickness (in)} \)

\[
F_{\text{optimal}} = 8.65 \frac{\rho 10^5}{A_m h} \quad (\text{Hz}),
\]

with the following units: \( \rho (\Omega \cdot \text{m}) \), \( A_m (\text{m}) \), and \( h(\text{m}) \) [6].

In cases when induction heaters cannot be considered to be electromagnetically long coils, but electromagnetically short inductors, the values of the optimum frequency will be higher than the values suggested according these formulas.

Tubes and pipes exposed to certain frequencies at high-power density could emit resonant sound waves of an appreciable magnitude exceeding the audible limit. Therefore,
when IH tubular workpieces, the audible noise can also be a dominant factor greatly affecting the selection of frequency.

Whenever we are dealing with tubes or pipes and, in particular, when simultaneously heating several tubes/pipes, each of them acts like a musical instrument (e.g., like pipes in an organ). Each tube has its own structural resonant frequency (SRF), which depends on the diameter, wall thickness, material, length, and other factors. When the frequency of the induction heater combines with the tube’s own resonant frequency (assuming that both frequencies are sufficiently close to each other), this could produce much greater combined acoustical or structural resonances, resulting in high-amplitude vibration and noise level. In other words, as a radio receiver transforms electromagnetic waves into an audible sound, somewhat similar mechanisms may occur, causing a tube/pipe to “act” as an amplifier or organ when dealing with certain frequencies and potentially producing an audible noise that can reach levels that may be a concern with respect to possible long-term hearing loss in workers working without adequate hearing protection.

When discussing the audible noise, we have to bear in mind that there are two major factors how humans can be affected by an industrial noise: its magnitude and its unpleasantness/discomfort level. For example, low-frequency audible noise (e.g., 50 Hz) could have a higher magnitude, but it might not be as unpleasant for the human ear as compared to a lower-magnitude noise at an elevated frequency (e.g., 1 kHz).

The decision on whether a noise will be reduced by choosing a different (higher or lower) frequency depends on the combination of the SRF of a particular pipe and the applied frequency of the induction heater.

Therefore, it might be beneficial to measure the pipe’s SRF by simply “hitting” it with a hammer and measuring the resonant audible noise of the pipe using some kind of audible receiver with the ability to detect the frequency and amplitude of the measured signal. As a result, more intelligent decisions can be made in determining whether a certain frequency would improve the noise level or not compared to a frequency that produces an unacceptable noise level. For example, if SRF of a certain workpiece is 300 Hz, then the further away that selected frequency is, the lower the noise that will be produced. In this case, 6 kHz would produce a noticeably lower noise compared to 1 kHz, for example. In contrast, if SRF is 5 kHz, then the use of 6 kHz will make it worse.

As discussed in Chapter 3, when heating a solid cylinder, regardless of frequency, there is no eddy current flow in its core (Figure 3.13a). However, when heating a hollow cylinder, there might be eddy currents flowing on both the O.D. and I.D. surfaces. Figure 6.54a shows the current density distribution along the wall thickness of a nonmagnetic tube using different frequencies.

While discussing the current density distribution along the wall thickness of a tube, it is imperative to mention a subtle phenomenon that does not have a wide practical use in induction tube heating. However, it is important to keep this phenomenon in mind from an academic perspective in order to have a better understanding of the physics of the process. This phenomenon has been discussed in Ref. [77].

In some cases, the current density distribution along the wall thickness of a hollow cylinder may have a U shape. This phenomenon takes place under certain conditions. The first condition deals with the fact that $\delta$ should be noticeably greater than the tube wall thickness. The second condition is that an internal magnetic flux concentrator be placed inside the heated tube. Figure 6.54b shows the distribution of current density along the tube wall thickness as a function of frequency, assuming that a highly permeable magnetic flux concentrator has been placed inside the tube.
Induction Mass Heating

As would be expected, in addition to the frequency and properties of the heated material, the eddy current distribution along the tube wall thickness depends on the air gap between the tube I.D. and the flux concentrator as well as the $\mu_r$ of the concentrator. Figure 6.54c shows the effect of $\mu_r$ on the current density distribution. An accurate evaluation of this phenomenon in a particular case can be carried out using numerical computer modeling.

6.7.2 In-Line IH of Tubes and Pipes and Their Applications

A continuous-feed multiple coil induction heater similar to in-line systems used for bar heating is a popular approach when it is required to through heat long tubular products. The range of heat treatment processes of steel tubes and pipes suitable for in-line IH include hardening and tempering. As an example, Figure 6.55 shows a time–temperature profile (Figure 6.55a) of the induction through hardening of carbon steel tubes (tube O.D. = 127 mm, wall = 12.7 mm, at 3 tons/h) consisting of three in-line coils and a water spray quench chamber (Figure 6.55b).

Gas quench bright annealing of stainless steel tubes is another example of the effective use of an in-line design [573]. Stainless steel tubing is used in decorative-type hardware, food processing, and other applications where a shiny bright appearance is important [573]. Stainless steel tubing is induction heated to a temperature of approximately 1100°C–1150°C and is then processed into a 6.1-m-long hydrogen–nitrogen gas quench tunnel. During the operation of the gas quench, nitrogen is used to purge the system of all oxygen. As purging continues, hydrogen is then fed into the system. Such an arrangement prevents the possibility of explosion that might occur should an excessive hydrogen and oxygen leak develop.

When designing bright annealing induction systems, it is important to have a sufficiently long quench tunnel so that when the tube exits the chamber, its temperature is below the oxidizing point; otherwise, the tube surface will tarnish as it reacts with the oxygen in the air. This phenomenon will not occur if the temperature of the stainless steel tube is below approximately 300°C as it emerges from the gas quench tunnel. Therefore, in order to be
on the safe side, it is often recommended that the exit temperature from the gas quench zone should not exceed 250°C and often it is less than 200°C.

To maximize circulation and, hence, quench intensity, quench gas is fed into two different locations in the tunnel. The tunnel has a water-cooled jacket that functions as a heat exchanger, helping to cool the quench gas that comes in contact with the tunnel’s inner surface. Although the entire line is airtight, the possibility of gas contamination exists at the entrance to the heating line and the exit from the quench tunnel. Consequently, the quench gas is kept under positive pressure. Hydrogen that “bleeds” is burned off at the entrance to the heating coil. In some cases, argon is used instead of nitrogen.

Stainless steel bright annealing systems often consist of a holding zone that is located between the induction heater and the quenching tunnel. The stainless steel tube maintains its temperature in this zone, ensuring the required microstructural conditions. A separate low-power induction coil or electric furnace can be used to hold the required temperature at the desired level by compensating for heat losses from the tube surface in the holding zone.

After exiting the quench tunnel, the tube temperature is much below the levels where surface contamination can occur during contact with air or moisture. Finally, the tube is cooled down for handling purposes using a water spray system.

The success of induction bright annealing of stainless steel tubes using a gas quench is greatly affected by the quality of the gas. As the dew point rises, the gas contains more moisture and the corresponding volume of hydrogen has to be increased. Otherwise, the process will not provide the required quality and surface appearance, because the chrome in the stainless steel and the moisture react together, forming an oxide, Cr₂O₃.

IH can be advantageously used for annealing of not only steels but also light metals, for example, copper alloys. Copper tubes are utilized in water plumbing, consumer goods,
transport, textile, and industrial machinery industries as well as for the production of tubing in the air conditioning and refrigeration industry. These industries dictate particular requirements for thin-wall ACR copper tubing [574–576]. These include the following:

- Small eccentricity of wall thickness
- Accurate dimensional tolerance
- Maximum heat transfer area
- Cleanliness of the tube inside wall
- Proper grain structure and annealing properties of the tube to allow easier bending

Because of several advantages, induction high-speed copper tube annealing systems (Figures 2.17 and 6.56) replaced the older bell-type and roller hearth furnaces [574–576]. This reduces not only the overall equipment cost but also the operating costs and provides greater productivity. The exposure to mechanical damage of fully annealed product handling is also eliminated.

After the tube is heated to the annealing temperature (for phos-deoxidized copper, it is approximately 700°C), it enters the holding or dwell zone to produce grain recrystallization. Thereafter, the tube enters the rapid quench station where the temperature is rapidly brought down to a conventional handling temperature. The typical layout of an induction basket-to-basket ACR copper tube annealing system is shown in Figure 6.56b.

When designing induction annealers for light wall copper tubing (i.e., wall thickness can be as thin as 0.3 mm) running at standard line speeds of 200 to 500 m/min (3.33 m/s to 8.33 m/s), automatic tension control is of the utmost importance to avoid tube marking. This is achieved by a variable-speed system, which constantly and precisely controls the copper tube tension during the annealing operation and minimizes any occurrence of jamming. Table 6.10 provides a typical annealing specification for a phos-deoxidized copper tube with an annealing grain size of 0.015 to 0.025 mm running at 300 m/min (5 m/s) rated speed.

**FIGURE 6.56**
Basket-to-basket induction annealing system of ACR copper tubing. (a) Image of actual system. (b) Layout of typical basket-to-basket ACR copper tube annealer. (Courtesy of Inductoheat-Australia, an Inductotherm Group company.)
Metallic and nonmetallic coating of tubular steels also often calls for the use of in-line IH. The main purpose of metallic coating of carbon steel tubes is to improve resistance to corrosion, oxidation, and abrasion.

Galvanizing is one of the metallic coating techniques. A fine zinc or zinc alloy layer is deposited on the O.D. surface of a steel tube, developing a metallurgical bond that provides a dual-action protection mechanism. A detailed discussion of the physics of metallic coating is described later in this chapter.

Nonmetallic coating represents a wide range of different coating techniques including, but not limited to, primers, paints, epoxies, polymers, heat-cured powders, and the like.

Figure 6.57b shows line pipe preheating coils made by Inductotherm-Australia. The line is designed for processing pipe with diameters from 0.05 to 3.05 m and wall thicknesses from 5 to 50 mm, and continuous pipe sections from 8 to 12 m.

### 6.7.3 Selective Heating of Tubular Products: Case Studies of Typical Applications

The ability of IH to concentrate the heat within a certain area of the workpiece is widely used to selectively heat tubular products. Such applications as localized stress relieving, brazing, parting, bending, coating, annealing of welds, and others are typical candidates for selective heating using electromagnetic induction.
Figure 6.57a shows induction coils and a solid-state power supply for heating of pipes used for oil and gas lines before the application of a three-layer polyethylene coating. This system is quite large. The coils are normally maneuvered into the heating position with the aid of casters or wheels, and jacked up for correct pass line height. They are housed in a steel frame to ensure robust performance and long life. Some systems are built with a coil mounted on a frame, permanently located in the line, and moved in and out of position by a crane. Typically, one coil is designed with the ability to heat several different pipe sizes.

The choice of coil length is another critical issue, which can be quite contradictory when designing IH systems for pipe’s selective heating applications such as tube parting or bending. It is quite clear that a shorter coil results in a smaller mass of metal to be heated and, therefore, leads to lower energy consumption. From another perspective, the coil electrical efficiency, among other factors, is also a function of the coil length. Shortening the coil length results in electrical efficiency reduction. Therefore, the choice of coil length is always a reasonable compromise.

When heating selective areas, it is sometimes desirable to have a short longitudinal transition zone, and the ability of a flux concentrator to localize the EMF can be a definite benefit here.

The ability of induction to provide selective heating is advantageously used for localized stress relieving and normalizing (Figures 4.92 and 6.58) as well as for tube end heating before swaging or upsetting or for pipe/tube bending applications where it is required to heat a narrow band around the area to be bent. Induction bending is usually performed on steel tubes with outside diameters varying in the range of 0.1 m (4 in.) to 1 m (40 in.). At the same time, there are examples of induction bending installations that are capable of bending much larger pipes (e.g., 1.5 m O.D. and even larger) [577].

The sketch shown in Figure 6.59 illustrates the principle of an induction bending machine. After positioning the pipe and firmly clamping both its ends, power is applied to the solenoid-type inductor that provides a circumferential heating of the pipe area to be bent. Upon achieving the appropriate temperature distribution ensuring sufficient ductility of the area where the bending will be taking place, the pipe is pushed forward through the coil at a certain speed. The pipe’s leading end, being clamped to the pivot arm, experiences a bending moment. The bending arm can pivot up to 180°. In induction bending of carbon steel pipes, the length of the heated area is usually within the range of 25 to 50 mm, with a required target temperature range from 800°C to 1080°C. As the pipe passes through the inductor, it bends within the hot and ductile bend area according to the radius

![FIGURE 6.58](image)

Induction pipe end heater. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
of the pivot radial arm while being supported on each side by a cold nonductile rigid section. Depending on the application, bending speeds can vary from 12 to 150 mm/min. In some bending applications, where larger radii are required, instead of a pivot radial arm, a set of bending rolls that provide a bending force is used [577–580].

After completion of the bending operation, the pipe is cooled down to ambient temperature using a water spray, forced air, or natural cooling in air. The process of stress relieving or tempering can be conducted in order to obtain the desired postbend properties of as-quenched steel pipes.

It is important to emphasize here that IH provides fast localized circumferential heating of selected areas of the pipe, consuming a minimum amount of energy compared to other hot bending processes that require heating the entire pipe. There are also other important benefits provided by induction bending. These benefits include high predictability of shape distortion (ovality) and wall thinning. Minimization and predictability of wall thinning are particularly critical when producing tubes and pipes for such industries as nuclear, or oil and gas lines with high-pressure requirements.

During bending, the outer side of the bend is in tension and has a reduced wall, while the inner side of the bend is in compression. When alternative heating is used to make the bend, the outer wall of the bend area is often reduced by as much as 20% or more, resulting in a corresponding reduction of the total pipeline pressure rating [624]. The pipe bend becomes the pressure-limiting factor in the total pipeline. With IH, this cross-section reduction is reduced to typically only 11%, thanks to even heating, an optimized bending program through a computerized bending machine, and a narrow ductile zone. Therefore, IH not only reduces production cost and increases the quality of the bend, but also reduces the total pipeline cost.

Other important advantages of induction bending deal with the fact that it is a non-labor-intensive process, has little effect on surface finish, and has the ability to bend small radii, producing multiradius curves/multiple bends in one pipe and bending of thin-walled tubes [577–580].

Rapid IH of the localized areas is used not only for bending steel tubes but also for bending some light metal hollow products, such as aluminum tubes. However, there is a different phenomenon involved in bending aluminum tubes compared to steel. According to the process of retrogression heat treatment (RHT process) that has been patented by Alumax Extrusions Inc. [581], IH provides rapid heating of selective areas of age hard-enable
aluminum alloy extrusions (i.e., 6000- and 7000-series alloys in various tempers and particularly the –T6 temper) to a temperature range from 315°C (600°F) to 538°C (1000°F) within a few seconds. The purpose of heating is to provide a full or partial softening of the heated zone after its rapid quenching to ambient temperature. Bending is typically carried out at room temperature with conventional tools and lubricants. It has been reported that even thin-walled aluminum tubes of 6061-T6 have been successfully bent using IH in combination with the RHT process to a radius-to-I.D. ratio of one tube diameter [581].

Seam annealing and stress relieving represent areas that utilize induction to provide selective noncircumferential heating of certain areas of pipes. Figure 4.92 shows a seam annealing inductor design that utilizes a split-return inductor for heat treating straight welded steel tubes. When the tube has been welded, the metallurgical structure in and around the weld zone (the heat-affected zone) is altered, producing a Widmanstatten-type structure, which occurs when metal has been heated to a sufficiently high temperatures and rapidly cooled. This structure is an undesirable heterogeneous brittle structure that consists of coarse elongated grains “shooting” into the matrix. Brittle martensitic areas are formed in the welded zone as a result of self-quenching (mass quenching) owing to the adjacent unheated cold areas. The narrower the heat-affected zone, the more intense the cold sink effect will be, the more brittle the welded structure will be formed.

The inductor is typically mounted in the mill line immediately after the welding and scarfing operations. In addition to the coil geometry, an inductor-to-tube gap, and frequency, the required heating power depends on the rate of tube processing and the width of the zone to be heated. Typically, the width of this zone can vary from 12 to 50 mm depending on pipe diameter, wall thickness, and process specifics.

When determining the required power, consideration must also be given to the residual temperature of the weld zone, keeping in mind that the amount of residual heat after induction welding is noticeably greater than the heat generated as a result of contact or laser welding.

The split coil or clamshell inductor shown in Figure 6.60 represents an inductor design that is used for full-body localized subcritical annealing of large oil and gas pipes having circumferential welds in a field environment. The coil is assembled around an existing pipe and disassembled after heating the weld area.

Section 4.6.3.2 discusses the development of a unique induction technology for stress relieving/tempering of tubular products fabricated from steels. This technology is referred

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FIGURE 6.60
Multiturn split coil (clamshell inductor) for pipe joint weld annealing.
to as Fluxmanager® Technology [357,358]. It represents a patented design of an induction heater, providing an effective way of controlling the end effect and providing the needed temperature uniformity for tempering/stress relieving of thick-walled carbon steel pipes used in the manufacture of high-quality connections for oil country tubular goods.

6.8 Slab, Plate, Bloom, and Rectangular Bar Heating

6.8.1 General Remarks

Electromagnetic induction is often applied for heating of noncylindrical workpieces (Figure 6.61). Workpieces of this general shape, including slabs, blooms, plates, RCS billets, and rectangular bar, are referred to in this section as slab. Specific reference is made to a particular shape where it applies.

Although there are several different coil arrangements available to heat a slab by induction, the great majority of applications apply rectangular solenoids (also referred to as longitudinal flux inductors) (Figures 2.3a, 2.24, 3.34, and 6.62). Because of the geometry of rectangular slab, IH of such workpieces has several features compared to the heating of cylinders. These include several electromagnetic effects and the peculiarity of heat transfer phenomena. Some of these phenomena will be outlined here; others were discussed in Section 3.1.7.

Suppose a slab is placed in an initially uniform magnetic field (Figure 3.34b). If the slab's length \( a \) and width \( b \) are much larger than its thickness \( d \), the electromagnetic field in the slab can be viewed as consisting of three zones: the central part, the area of longitudinal end effect, and the area of transverse edge effect (Figure 3.34b) [1,44,79,80,84,582–584].

In the central part, the EMF distribution corresponds to the field in an infinite plate. Analysis can be simplified with reasonable accuracy assuming that the electromagnetic end and edge effects have two-dimensional space distributions excluding only the zone of three-edge corners where the field is three-dimensional and the corresponding EMF distribution is the result of a mixture of both the electromagnetic end and edge effects (see Section 3.1.7).

![FIGURE 6.61](image-url)

Electromagnetic induction is often applied for heating of noncylinder workpieces. (a) Progressive heating of RCS billets; (b) continued heating of rectangular bars; (c) oscillating heating of slabs. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
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In the longitudinal flux IH of long or continuously fed rectangular slabs, the challenge in obtaining heat uniformity is caused by determining the proper combination of skin effect, electromagnetic edge effect, and electromagnetic end effect.

The core-to-surface temperature difference in the central area is a result of skin effect. The temperature difference between the edge area and the central part of the slab is formed by the combination of the electromagnetic transverse edge effect and additional heat losses at the edge area. Because of the edge effect, a surplus or shortage of power in the edge area can occur, leading to corresponding heat nonuniformities (Figure 4.215). With the proper choice of design parameters, it is usually possible to obtain the proper power density distribution that will provide a reasonably uniform (a quasi-uniform) temperature profile along the slab width. In this case, the additional heat losses at the edge area are compensated for by the heat source surplus generated there owing to the electromagnetic edge effect.

The transverse edge effect can be conveniently studied using $B$ or $H$ field representation (Figure 6.63). In contrast, it is more convenient to study the electromagnetic end effect using $A$ or $E$ field representation.

Frequency selection affects temperature profiles along the length and thickness and across the width. When heating a rectangular-shaped body, it is convenient to quantify the skin effect in the slab, using the ratio of $d/\delta$, where $d$ is the thickness of the slab. More uniform temperature profiles along the slab thickness (with reduced “surface-to-core” differential) correspond to a lower ratio of $d/\delta$, but there is a limit. If $d/\delta$ is noticeably greater than 8, the temperature distribution along the slab thickness will be quite nonuniform. Cycle time increase in combination with the power density reduction and power pulsing helps obtain a more uniform surface-to-core temperature distribution thanks to thermal conduction. At the same time, an increase of the cycle time leads to an increase in heat losses and could potentially result in localized cold spots particularly in the 3-D corner.

Importantly, as in the case of heating cylinders, the choice of frequency also affects coil electrical efficiency ($\eta_{el}$). There is an optimal frequency ($F_{el.eff}$) that corresponds to the maximum value of $\eta_{el}$. Frequency higher than the optimal will only slightly change the efficiency. If the chosen frequency is noticeably lower than the optimal value ($F_{el.eff}$), the electrical efficiency can dramatically decrease owing to cancellation of the induced currents circulating in the opposite sides of the slab cross section.

The frequency that corresponds to the maximum $\eta_{el}$ while heating infinitely wide slabs can be determined as follows [79,80,584].
A nonmagnetic slab or a magnetic slab heated above the Curie temperature:

\[
\frac{d}{\delta_{\text{non-magn.}}} \approx 3 - 3.5. \tag{6.9}
\]

For a magnetic slab:

\[
\frac{d}{\delta_{\text{magn.}}} \approx 2.8 - 3.2, \tag{6.10}
\]

where \(\delta_{\text{non-magn.}}\) is the current penetration depth in a nonmagnetic slab, and \(\delta_{\text{magn.}}\) is the current penetration depth in a magnetic slab.

It should be also noted that the \(F_{\text{eff.}}\) might not produce the most uniform heating.

As expected, the smaller air gaps and tighter windings of coil turns improve the \(\eta_{\text{el.}}\). The higher ratio of \(b/d\) (where \(b\) is the width of the slab) also corresponds to the higher \(\eta_{\text{el.}}\) (assuming the same slab-to-coil coupling).

In the past, coil calculations for heating blooms and bars/billets with a square cross section were conducted using formulas for equivalent cylinders (cylinders with equivalent diameters). An error in such calculations of coil electrical parameters is usually within 6% to 10%. The calculation error increases with a higher ratio of \(b/d\). Such an assumption should not be used if \(b/d > 1.2\). Numerical computer modeling offers better results (Figure 4.215).

As discussed in Section 3.1.6, any current-carrying conductor placed in an EMF experiences a force. The intensity of this force and subsequent magnetic pressure in some cases...
might be so significant that it can result in coil shape distortion and even bending of copper buses and tubing. Electromagnetic vibration and industrial noise are other undesirable side effects of these forces. Rectangular inductors for heating slabs made of low electrical resistivity materials (e.g., Al, Mg, or Cu alloys) that apply high power densities are particularly sensitive to this problem. Therefore, in order to provide a rigid and reliable coil design, the existence of EMFs and magnetic pressure should be taken into consideration, particularly with induction coils that have noncylindrical shapes. Cylinder coils have a greater natural rigidity. This text is not intended to provide a detailed discussion of this subject. The nature of EMFs and magnetic pressure as well as acoustic vibration in IH applications is discussed in Ref. [585].

6.8.2 Longitudinal Electromagnetic End Effects of Rectangular Workpiece

As discussed in Section 3.1.7, the longitudinal electromagnetic end effect in the static IH of rectangular workpieces is quite similar to the end effect that occurs in cylinders. When heating slabs that travel “end to end” through the induction coil in a continuous manner, the electromagnetic end effect does not lead to temperature nonuniformity (except the leading end of the first slab and the trailing end of the last slab) because each transverse section of the slab experiences the same magnetic field with respect to time as the slab proceeds through the heating line. It is more convenient to review the end effect appearance considering static heating applications.

6.8.2.1 Nonmagnetic Slab

Similar to cylinders, the electromagnetic end effect of a nonmagnetic slab is defined by several variables, including

\[
\begin{align*}
    d/\delta & = \text{skin effect} \\
    \sigma/d & = \text{normalized coil overhang} \\
    D/d & = \text{thickness ratio} \\
    K_{\text{space}} & = \text{space factor of coil turns}, \\
    P & = \text{power density}
\end{align*}
\]

where \( \sigma \) is the coil overhang, \( D \) is the height of the horizontal induction coil (coil opening), and \( K_{\text{space}} \) is the space factor of turns winding.

Higher frequencies and larger coil overhangs lead to the surplus of additional heat sources at the slab end, causing overheating the end area of a nonmagnetic slab.

When the frequency is relatively low (skin effect is not pronounced) and coil overhang is insufficient, instead of a surplus, a heat source deficit at the slab end will occur. By the proper selection of coil overhang and frequency, it is usually possible to obtain a condition where the surplus of heat sources caused by the electromagnetic end effect can be offset by the additional heat losses from the slab's end producing reasonably uniform heating.

Figure 6.64a shows the normalized power distribution in the end zone of an aluminum slab for different coil overhangs, where \( P_c' \) corresponds to the integrated power densities in the slab central area. The distribution of normalized power density was obtained by integrating the volumetric power densities (in kilowatts per unit volume) along the slab thickness.
In this case study, the power density distribution along the slab length can be considered reasonably uniform if $\sigma/d = 0.7$ (approximation). Under this condition, there is a local surplus of heat sources at the slab butt end; however, in the adjacent region, there is a localized power density deficit. Therefore, thermal conductivity will help equalize this localized heat source difference. Besides that, the butt end area of the slab has greater surface heat losses (owing to thermal radiation and convection) compared to its central area. These additional heat losses will also somewhat compensate for the surplus of power density, resulting in a nearly uniform temperature distribution.

In the case of a nonmagnetic slab, with a positive coil overhang $\sigma/d > 0$, the power density always increases toward the end. This is true for any frequency and any nonmagnetic metallic material. However, this does not automatically mean the heat surplus will be at the butt end because the heat losses from the slab end can exceed the surplus of power. In addition, a region with a power density deficit just behind the butt end area might exist at low ratios of $\sigma/d$, overpowering the localized heat surplus at the slab’s butt end. Therefore, in cases such as this, an underheating of the slab ends can occur regardless of the localized power density surplus there.

### 6.8.2.2 Magnetic Slab

The end effect in a magnetic slab also has many similarities compared to heating magnetic cylinders. As discussed in Section 3.1.1.2, ferromagnetic materials have a tendency to gather the imaginary magnetic flux lines because of $\mu_r$. In engineering calculations, $\mu_r$ of the nonmagnetic slab is considered as equivalent to that of air and it is assigned the value of one. By contrast, $\mu_r$ of carbon steel can vary, for example, from 1 to more than 300, depending on the magnetic field intensity, temperature, and frequency (Figure 3.8a). The electromagnetic end effect in a ferromagnetic slab is mainly affected by two factors (as is also the case of IH of magnetic cylinders):

![Normalized power distributions in the end zone attributed to the electromagnetic end effect of a nonferrous slab for different coil overhangs (a) and ferromagnetic slab for $\sigma/d = 1.5$ (b).](image-url)
1. The demagnetizing effect of eddy currents, which tend to force the magnetic field out of the slab
2. The magnetizing effect of the surface and volumetric currents, which have a tendency to gather the magnetic field within the slab

The first factor causes an increase in power density at the slab’s end. The second factor causes a reduction of the heat source generation there. Therefore, unlike those of the non-magnetic slab (Figure 6.64a), the ends of the ferromagnetic slab, even with large coil overhang, may have either heat surplus or deficit. Figure 6.64b shows that there will be a greater heat source shortage at the slab end area with higher $\mu_r$. A decrease of $\mu_r$ leads to a reduction of the power deficit in the end area. Therefore, instead of the power shortage (e.g., $\mu_r > 40$, for conditions of the case shown in Figure 6.64b), a power surplus can occur ($\mu_r < 20$). In this case, the end effect in a ferromagnetic slab will be approaching the end effect of a nonmagnetic one.

Since the $\mu_r$ of the ferromagnetic slab varies along its length, the skin effect $d/\delta$ also varies accordingly. Therefore, the curves shown in Figure 6.64b represent a simplified case owing to the assumption of constant $\mu_r$.

In conclusion, because of the electromagnetic end effect that occurs with statically heated slabs, plates, or blooms with appropriately selected process parameters, it is possible to obtain a sufficiently uniform temperature distribution along the slab length by choosing the proper coil overhang, heat intensity, and frequency (3-D corner requires special consideration). However, if the skin effect is not pronounced and low power densities are used, then the end area of a ferromagnetic slab might be noticeably under heated at any coil overhang.

In order to provide the needed temperature uniformity along the length of the slab, it might be necessary to use special means to control the EMF in the end area including those illustrated in Figure 4.153.

If the ferromagnetic slab is heated from room temperature to temperatures exceeding the Curie point, then the end effects of both the magnetic and nonmagnetic slab occur sequentially. In the beginning of heating, only the end effect of a magnetic body will occur. When the slab surface temperature exceeds the Curie point but the near surface areas are still ferromagnetic, a mixture of both magnetic and nonmagnetic end effects will take place. When the temperatures of surface and subsurface regions exceed the Curie point, then the end effect of a nonmagnetic slab occurs.

### 6.8.3 Electromagnetic Transverse Edge Effect

As mentioned earlier, in addition to the distortion of the magnetic field in the slab’s end areas, a similar distortion occurs at its edges (the transverse cross section). This phenomenon is referred to as the electromagnetic transverse edge effect (Figure 3.34b) [76,78–80,582–584,625] that plays a major role in obtaining the required temperature profile across the slab width (Figure 4.215).

#### 6.8.3.1 Transverse Edge Effect of Nonmagnetic Slab

Assuming homogeneous electrical properties, the maximum value of the eddy current density is located on the surface of the slab’s central part (it does not, however, mean that the maximum temperature is always located there). The more pronounced the skin effect, the better the path of induced eddy currents matches the contour of the slab. Figure 6.65a illustrates the distribution of the electric field intensity in the slab’s transverse cross section with pronounced skin effect ($d/\delta = 10$) and when skin effect is not pronounced ($d/\delta = 3$).
If the skin effect is pronounced \((d/\delta > 5)\), then the power densities are approximately the same along the slab perimeter, except in the corner areas (Figure 6.65a, bottom half), where the distortion of induced power densities takes place.

Even though the surface heat losses at the edge and corner areas are greater than at the central part, the corners and edge areas can still be overheated. This occurrence can be explained in the following simplified way: in the central area of the slab, the heat sources penetrate from two surfaces. In contrast, in the slab’s edge areas, the heat sources penetrate from two surfaces and the edge side. The phenomenon of edge or corner overheating usually occurs in the IH of magnetic steel, aluminum, and copper slabs where the skin effect is typically highly pronounced.

If the skin effect is not pronounced \((d/\delta < 3)\), then underheating of the corners and edges may occur (Figure 4.215). In this case, the path of eddy currents in the slab cross section does not match the contour of the slab and most of the induced currents close their loops earlier, without reaching the corners and the edge areas (Figure 6.65a, top half).

As a result, the generated heat sources in the edge areas will be reduced compared to the corresponding values in the central part of the slab. For example, in IH of thick titanium slabs (using relatively low frequency), in the final heating stage, the temperature of the corners and edge areas could often be 20% lower compared to the temperature of the slab’s central part requiring dual-frequency heating.

As an example and in order to qualify a distortion of power density distribution owing to transverse edge effect, Figure 6.65b shows a normalized power density distribution within a transverse cross section of a nonmagnetic slab for two different cases, \(d/\delta = 3\) (top) and \(d/\delta = 10\) (bottom).

From an electromagnetic perspective, the slab’s corners should be considered as special areas. Because of the principle of eddy current discontinuity, no currents are induced in the sharp corner of the slab applying a solenoid coil. However, regardless of this phenomenon, a heat surplus may take place in corners when the skin effect is pronounced.

It is convenient to use the specific power density \(P'_t \text{ [W/m}^2\text{]}\) as a parameter to quantify the transverse electromagnetic edge effect in the slab transverse cross section. \(P'_t\) can be obtained by integrating the volumetric power density \(P \text{ [W/m}^3\text{]}\) along the slab thickness and plotting its distribution across the width of the slab.
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\[ P'(X) = \int_0^{d} P(X, Y) dY \] (6.11)

Figure 6.66a shows the distribution of the normalized power \( P'/P'_{tc} \) across the width of the nonmagnetic slab, as a function of the \( d/\delta \) and \( b/d \) (where \( P'_{tc} \) is the integrated power density in the central part of the transverse cross section of the slab) \([582,584]\).

If the skin effect is not pronounced (i.e., \( d/\delta < 2.5 \)), a marked power reduction is observed in the near-edge area resulting in a noticeable deficit of heat sources. If surface heat losses are absent and \( d/\delta \approx 3.14 \), the power deficit in the near-edge area is approximately compensated for by its surplus near the edge as shown in Figure 6.66a.

Studies show \([584]\) that the edge effect area does not extend from the slab edge toward its central part more than the slab thickness and is usually (1.5 to 4.0)\( \delta \) long. Normally, the length of the edge effect zone does not depend on the width of the slab, particularly when \( b/d > 4 \). Edge effect zones from both sides will overlap when \( b/d < 2 \).

6.8.3.2 Specifics of the Transverse Edge Effect of a Magnetic Slab

Realistically speaking, the \( \mu \) of a magnetic slab changes along its thickness, length, and width; therefore, the skin effect \( d/\delta \) varies throughout the slab’s body as well. In order to simplify the analysis of the edge effect in a magnetic slab, the \( \delta \) is calculated using the

![Diagram showing the distribution of the normalized power across the width of the nonmagnetic slab.](a)

**FIGURE 6.66**
The distribution of the normalized power \( P'/P'_{tc} \) across the width of the nonmagnetic slab, as a function of the skin effect \( d/\delta \) and ratio \( b/d \) (a) and a comparison of the electromagnetic transverse edge effect in magnetic and nonmagnetic slab (b).
6.8.3.3 Dynamics of Transverse Edge Effect during the Heating Cycle

In order to avoid excessive temperature nonuniformity along the perimeter of the rectangular body, it is often beneficial to use a dual-frequency approach. With a dual-frequency approach, a low frequency is used during the initial heating stage when most of the slab remains ferromagnetic. After the surface temperature exceeds the Curie point, a higher frequency is applied. The criteria for applying a dual-frequency approach for heating rectangular-shaped bodies is quite different compared to heating cylinders.

When heating solid cylinders, the principal reason for using a dual-frequency approach is to avoid eddy current cancellation at the final heating stage. However, when IH rectangular workpieces, there is an additional criterion for using a dual-frequency approach that deals with the need to control the transverse edge effect and, thus, the ability to provide the required temperature distribution along the slab’s perimeter.

Therefore, in slab, plate, or rectangular bar heating applications, a dual- or a multifrequency design concept allows combining the high electrical efficiency, short cycle time, and in-depth heating with the capability to achieve the required temperature uniformity along the perimeter of a rectangular body.

Case Study. A dual-frequency design has been successfully used in the IH of steel RCS bars. The induction system consists of nine in-line coils and two power supplies: 600 kW/0.5 kHz and 300 kW/1 kHz. The rectangular steel bars are 100 mm² and 3 m long with the overall length of the coil assembly being 9 m. The bars are heated from room temperature up to 650°C using 0.5 kHz and then 1 kHz is used to increase the temperature to 1120°C.

Another example is shown in Figure 6.67, which illustrates 2-D temperature profiles in a quarter of a 0.15-m RCS stainless steel bar with a 20-mm radius using a dual-frequency approach [84]. Significant temperature gradients occur within the bar cross section. It is important to have a clear understanding of the magnitude of these gradients during the intermediate and, in particular, during the initial, heating stage. With intensive heating, longitudinal and transverse cracks might occur as a result of the excessively large thermal stresses caused by different magnitudes of temperature and temperature gradients. Corner radiuses make a marked impact in temperature distribution.

6.8.4 Design Concepts of Heating Rectangular Workpieces: Case Studies of Commercial Installations

Depending on the process requirements, there are several designs of induction systems for heating rectangular workpieces: static heating, in-line continuous/progressive heating, and oscillating heating (Figure 6.6). The name of each design is fairly self-explanatory and indicates the specifics of slab movement during the heating cycle.

6.8.4.1 Static Heating

According to static heating, a rectangular workpiece is statically heated without any movement during the heating cycle. This design concept is very similar to the static heating of cylindrical billets. An induction system can consist of one or several coils. Figure 6.68a
**FIGURE 6.67**
Temperature profiles in a quarter of a 0.15-m RCS stainless steel (3xx-series) bar with a 20-mm radius using a dual-frequency (500 Hz and 3 kHz) approach. Target temperature is 1315°C. Temperature distribution at the end of (a) initial, (b) intermediate, and (c) final heating stages reveals transient and final heat patterns (°C). (From V. Rudnev, Successful induction heating of RCS billets, *Forge*, July, 15–18, 2008.)
shows an example of a multiple coil system that statically heats 0.15-m (6-in.) carbon steel square (RCS) bars to 1250°C (2282°F). This system consists of a 2000-kW/1-kHz power supply feeding six inductors. The number of inductors depends on the required production rate.

6.8.4.2 In-Line Continuous Heating

Continuous slab heating assumes that the slab is being progressively/continuously moved through the IH line. The continuous heating is often used for slab reheating after continuous casting. In such an application, the inductor is located just before the mill and should be able to compensate for the previous nonuniform cooling effects and surface heat losses in the continuously cast slab, strip, or plate providing the hot mill with a uniformly reheated workpiece.

One of the challenges in developing induction reheating systems after continuous casting deals with nonrectangular (i.e., trapezoidal) cross sections of bars and slabs and with the nonuniform temperature profiles that exist before the reheating stage.

At this point, it would be beneficial to provide a case study of a continuous in-line induction reheater of trapezoidal cross section continuously cast long aluminum bars [563]. It was necessary to reheat both rectangular- and trapezoidal-shaped aluminum alloy bars after continuous casting before rolling. An original, line frequency induction reheater was chosen first, one that required no special power supply, which held down the cost.

However, line frequency IH falls short of several process requirements. Because of limited temperature control capability and an inability to meet the temperature uniformity requirements (particularly in the case of bars with trapezoidal cross sections), it was particularly difficult to handle the required temperature of the sharp corners.

In addition, because of the nature of the continuous casting process, the temperature profile within the bar cross section entering the reheating stage was measurably nonuniform. The sharp corners were noticeably cooler than the internal regions.

The aluminum manufacturer requested Inductoheat, Inc. to analyze a possible improvement to the existing line frequency IH system. After an extensive evaluation based on computer modeling using proprietary software and applying experience gained from previous jobs, it was found that for that particular geometry of trapezoidal-shaped aluminum bars, the optimal choice was a longitudinal flux coil operating at 700 Hz/750 kW [563].

![Examples of induction systems for heating 0.15 m RCS steel bars (a) and aluminum bars with trapezoidal cross sections (b). (From V. Rudnev, W. Albert, Continuous aluminum bar re-heating prior to reducing mill, 33 Metal Producing, January, 50, 1995.)](image-url)
The net result was a compact induction reheating system that requires minimum floor space. The coil length was approximately 1.5 m long (Figure 6.68b). The induction system was able to process the cast aluminum alloy bars of both rectangular and trapezoidal cross sections at a production rate of 12.8 m/min. The final temperature after induction reheating was 520°C ± 6°C [563].

6.8.4.3 Oscillating Heating

According to the oscillating design concept, the slab moves back and forth (oscillates) inside the induction heater during the heating (Figure 6.6c) with a certain oscillation stroke. Oscillating heating provides several principal benefits compared to continuous or progressive in-line heating, including the following:

- Minimum shop floor requirements while providing a high production rate
- Relative ease of operation in both the heating and holding modes
- System flexibility
- Higher overall efficiency owing to minimized radiation heat losses

The nature of oscillating induction heaters requires proper handling of the end and edge effects; otherwise, the slab end and edge areas could have noticeably different temperatures compared to their central area and internal regions. In addition, the phenomenon of “thermal striping” could appear when an improper process recipe is used.

If the initial temperature of the slab is uniform, then, in order to provide a uniform final temperature distribution within the slab, it is necessary to ensure that each region along the slab width and length absorbs the same amount of energy during the process cycle. After continuous casting, a temperature distribution within the slab is substantially non-uniform, depending on slab geometry and features of the casting process (i.e., production rate and specifics of cooling). Slab edges tend to cool faster than the central areas and, particularly, its core.

As an example, Figure 6.69 shows an initial temperature distribution in a quarter of a continuously cast 0.22-m-thick slab before induction reheating. Therefore, it is necessary to

![FIGURE 6.69](image)

Nonuniform temperature distribution (°C) in a quarter of the continuously cast world’s largest steel slab before induction reheating.
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redistribute energy induced within the slab in such a way that it would allow compensating for its nonuniform initial temperature profile.

The world’s largest oscillating induction heater (Figure 6.61c) was engineered and manufactured by Inductotherm Corp. for Geneva Steel, Utah, in August 1995 [568]. After installing the world’s largest continuous caster, Geneva Steel was looking for a method to reheat large slabs that required 800 to 1000 PIW (pounds per inch width). This reheating system was to feature the lowest capital cost possible, bringing the added capacity online in the shortest time possible. Slabs were produced in a continuous caster, which was capable of producing 1.8-m-wide (71-in.-wide) through 3.2-m-wide (126-in.-wide) single slabs or 1.07-m-wide (42-in.-wide) through 1.6-m-wide (63-in.-wide) twin cast slabs. Figure 2.24 shows an induction reheater of 1.6-m-wide (63-in.-wide) twin slabs. All slabs were 0.22 m (8.7 in.) thick [568]. It was required that an induction system should be in-line with the existing caster and the rolling mill.

This task was accomplished by a 42,000-kW induction oscillating system (Figures 2.24 and 6.61c) with the capacity to reheat 540 short tons per hour from a bulk input temperature of 1090°C (1994°F) to a bulk output temperature of 1260°C (2300°F). An example of non-uniform temperature distribution prior to induction reheating is shown in Figure 6.69. This unique induction slab heating system was designed, manufactured, and delivered to Geneva Steel within a 5-month period [568]. Geneva Steel completed construction and installation within 1 month. Total time from inception of the contract to beginning start-up of the equipment was 6 months.

The induction system is capable of reheating two slabs side by side, four slabs side by side and end to end, three slabs end to end, two slabs end to end, or one large single slab. This feature emphasizes the flexibility of this system. The overall length of the reheater is 14 m and the overall width is 4 m.

Seven rectangular solenoid coils are placed in-line with one after another at a distance of 1.71 m center to center. Each coil can deliver up to 6000 kW /110 Hz of power (Figure 2.3a). Slabs are processed through an oscillation stroke of 1.71 m and continue to oscillate until the required time at the surface temperature, time at holding power, and mill push rate are met. Slab holding capability can also be provided if required.

Slabs exit the induction reheater one at a time as they precede to the rolling mills; therefore, slabs must enter the reheater one at a time, which requires a split roll line with individually driven rolls. Since slabs enter the reheater individually, they are at different bulk heat values. Control is focused on only the hottest slab in the furnace, thereby avoiding the possibility of accidentally overheating.

Since many slab heating systems require a substantial amount of power, one of the obvious concerns when designing a multi-megawatt system is the possibility of noticeable external magnetic field exposure. Care must be taken in the system design to prevent the drive systems and supporting framework from being affected by electrical noise or IH by an external magnetic field. As stated earlier, the IH system of the world’s largest carbon steel slab shown in Figures 2.24 and 6.61c utilized a total power of 42 MW. The system comprises seven coils of 6 MW each. The Inductotherm Corp. has developed patented magnetic shunts for a dramatic reduction of the external EMF outside the coils. Without magnetic shunts, the magnetic field would spread around the coil supporting structure. Magnetic shunts allow containment of the field inside the coil somewhat similar to the case study shown in Figure 6.10. Although the power delivered to each coil is approximately 6000 kW, the level of the magnetic field exposure outside the coil is quite low. Actual field measurement indicates 20 μT at a 0.3-m range from the coil [568].

Magnetic shunts concentrate energy directly into the slab, resulting in a coil electrical efficiency increase of 3% to 5% compared to the inductors without shunts. In addition, the
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coil with magnetic shunts has a significantly higher mass than the coil without shunts. This added mass greatly reduces the mechanical resonance frequency and vibration on the inductor, which in turn increases the inductor’s rigidity.

Figure 6.62 shows a variety of Inductotherm’s rectangular inductors used in oscillating heating applications of slabs 0.1–0.2 m (4–8 in.) thick, 0.76–1.5 m (30–60 in.) wide, and 3.6–7.2 m (12–24 ft) long. This technology has been used for heating not only steel slabs but also titanium alloys (700°C–960°C or 1300°F–1750°F), zirconium alloys (20°C–700°C or 70°F–1300°F), and other metallic materials.

6.9 In-Line IH of Strip, Sheet, Plate, Thin Slab, and Transfer Bar

IH of thin slabs, plates, and strips is similar to the heating of rectangular bars and thick slabs, which was discussed in Section 6.8. At the same time, there are some specific features regarding design concepts, selection of process parameters, and application specifics that make it unique. In this section, we do not repeat the basic principles and phenomena, which were already discussed above. It is assumed that the reader is already familiar with them.

In this section, we use the term strip, assuming that all discussions hold true for other workpieces of similar shape (e.g., plate, sheet, etc.), unless mentioned specifically.

Induction strip-heating applications include but are not limited to process annealing, galvanizing, galvannealing, galvaluming, preheating before the reducing mill, tempering, stress relieving, paint curing, lacquer coating, drying, and others [1,78–80,586–588,620,664].

Intensive use of IH of strips has been observed in strip-coating applications. The popularity of coated metallic strips and in particular low-carbon steel strips has soared through the efforts of strip producers to find more durable and environmentally friendly coatings (both metallic and nonmetallic).

One of the main goals of any type of coating is to isolate the carbon steel from corrosive media, forming a corrosion protective barrier. At the present time, it is possible to apply solvent-based, water-based, and powder coatings as well as coatings with no solvents at all. Each approach requires different process specifics in terms of pretreatment and curing. For example, during the last decade, the use of clear coats has increased dramatically to provide basic protection from finger marking on plain metallic-coated material.

Such metal-coating processes as galvanizing, galvaluming, galvannealing, and tinning represent some of the most frequently used metallic-coating applications and occupy the highest volume of coated metal strips used for the needs of the domestic appliance, automotive, and construction industries. This is the reason why the following discussion is focused on these processes.

6.9.1 Strip-Coating Processes

6.9.1.1 Metallic Coating of Strips (Galvanizing, Galvaluming, Galvannealing, and Tinning)

The main purpose of metallic coating of carbon steel strip is to improve resistance to oxidation, corrosion, and abrasion. These goals can be achieved by depositing a layer of a certain metal or alloy on the strip surface. Pure zinc and zinc alloys are the most frequently used metallic coatings. Aluminum and its alloys are also used in combination with zinc to improve corrosion protection and/or formability.
Metallic coating has a dual-action protection mechanism [586–592].

1. In order to prevent the surface of a carbon steel strip from rusting and oxidation when it is exposed to air and humidity, the metallic coating simply provides a physically and chemically stable barrier that isolates the steel surface from contact with oxygen, water, or aggressive media.

2. In addition to serving as a physical protection barrier, metallic coating conducts the anodic reaction to steel (the so-called cathodic protection). As a result of cathodic protection, the process of galvanic corrosion of the less corrosion-resistant metal of a galvanic cell (a metal with greater negative potential) will experience more intense corrosion while galvanic corrosion of the corrosion-resistant metal (metal with more positive potential) will decrease.

Therefore, if the protective metallic coating layer is accidentally disrupted (i.e., attributed to microporosity or small scratches), then because of the galvanic reaction, the metallic protective layer becomes the anode and the steel acts as the cathode. As a result, instead of developing a rust formation in the steel, the metallic coating layer undergoes an electrochemical reaction when a positive current starts to flow from the metallic coating through the medium that acts as an electrolyte to the carbon steel providing an electrolytic or cathodic protection. The slow rate of zinc corrosion compared to corrosion of iron ensures long-lasting protection of carbon steel coated with zinc. Figure 6.70 illustrates the “self-healing” mechanism of the rust prevention action of metallic coating as compared to a nonmetallic coating. The life of a galvanized coating depends on the coating thickness, type of environment, and alloy used for coating in comparison to base metal.

It is wise to remember that not all metals are suited to provide such an active electrochemical protection of the carbon steel. Only metals that have an electronegative position with respect to carbon steel potential can do so. If two metals are coupled to create an electrochemical cell, then the potential difference is responsible for the corrosive reaction. The greater the difference in the potentials, the more intense the galvanic corrosion of the metal with the most negative potential compared to the base metal. Table 6.11 shows potentials and types of reactions for selected metals in the electrochemical (galvanic) series [566].

The galvanization process applies the above-described advantages of metallic coating. A thin layer of pure zinc or zinc alloy is deposited on a carbon steel surface providing a metallurgical bond.

Continuous galvanizing lines can apply hot dip or electrolytic processes. According to the electrolytic galvanizing, zinc is electrolytically deposited on the strip surface. This process is relatively expensive and typically handles strip widths of 0.5 to 1.8 m. One of the main shortcomings of electrolytic galvanizing is its ability to provide only a light coating. Maximum coating thickness is approximately 0.0045 mm.

The continuous hot dip galvanizing process consists of three stages [567]. During the initial stage, the process of cleaning and pickling takes place. During this stage, different types of surface contaminants (including grease, dirt, oil, mill scale, lubricant residues, etc.) are removed. Annealing or heat treating of the steel that is preheated to a certain temperature represents the second or intermediate stage. During the final stage of the hot dip galvanizing, the heated strip passes through a molten zinc pot where the zinc coating is applied (Figure 6.71a). As a result of a metallurgical reaction that takes place between a molten alloy coating and hot carbon steel, an alloy layer is created. This alloy layer binds the coating to the carbon steel.
Induction Mass Heating

**FIGURE 6.70**
Comparison of metallic and nonmetallic coatings.

**TABLE 6.11**
Electrochemical (Galvanic) Series of Selected Metals

<table>
<thead>
<tr>
<th>Metal</th>
<th>Reaction</th>
<th>Potential, V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>$\text{Ag}^+ + e^- \rightarrow \text{Ag}$</td>
<td>+0.8</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$\text{Al}^{+3} + 3e^- \rightarrow \text{Al (0.1f NaOH)}$</td>
<td>−1.706</td>
</tr>
<tr>
<td>Gold</td>
<td>$\text{Au}^+ + e^- \rightarrow \text{Au}$</td>
<td>+1.68</td>
</tr>
<tr>
<td></td>
<td>$\text{Au}^{+3} + 2e^- \rightarrow \text{Au}^{+1}$</td>
<td>+1.29</td>
</tr>
<tr>
<td></td>
<td>$\text{Au}^{+3} + 3e^- \rightarrow \text{Au}$</td>
<td>+1.42</td>
</tr>
<tr>
<td>Chromium</td>
<td>$\text{Cr}^{+2} + 2e^- \rightarrow \text{Cr}$</td>
<td>−0.557</td>
</tr>
<tr>
<td></td>
<td>$\text{Cr}^{+3} + e^- \rightarrow \text{Cr}^{+2}$</td>
<td>−0.41</td>
</tr>
<tr>
<td></td>
<td>$\text{Cr}^{+3} + 3e^- \rightarrow \text{Cr}$</td>
<td>−0.74</td>
</tr>
<tr>
<td>Copper</td>
<td>$\text{Cu}^+ + e^- \rightarrow \text{Cu}^+$</td>
<td>+0.522</td>
</tr>
<tr>
<td></td>
<td>$\text{Cu}^{+2} + e^- \rightarrow \text{Cu}^+$</td>
<td>+0.158</td>
</tr>
<tr>
<td></td>
<td>$\text{Cu}^+ + 2e^- \rightarrow \text{Cu}$</td>
<td>+0.34</td>
</tr>
<tr>
<td>Iron</td>
<td>$\text{Fe}^{+2} + 2e^- \rightarrow \text{Fe}$</td>
<td>−0.409</td>
</tr>
<tr>
<td></td>
<td>$\text{Fe}^{+3} + 3e^- \rightarrow \text{Fe}$</td>
<td>−0.036</td>
</tr>
<tr>
<td>Magnesium</td>
<td>$\text{Mg}^{++} + 2e^- \rightarrow \text{Mg}$</td>
<td>−2.375</td>
</tr>
<tr>
<td>Lead</td>
<td>$\text{Pb}^{+2} + 2e^- \rightarrow \text{Pb}$</td>
<td>−0.126</td>
</tr>
<tr>
<td>Titanium</td>
<td>$\text{Ti}^{+2} + 2e^- \rightarrow \text{Ti}$</td>
<td>−1.63</td>
</tr>
<tr>
<td></td>
<td>$\text{Ti}^{+3} + e^- \rightarrow \text{Ti}^{+2}$</td>
<td>−2.0</td>
</tr>
<tr>
<td>Zinc</td>
<td>$\text{Zn}^{+2} + 2e^- \rightarrow \text{Zn}$</td>
<td>−0.763</td>
</tr>
</tbody>
</table>

Electromagnetic induction can be effectively applied to heat the strip before entering the coating pot as well as heating of a melted zinc pot (Figure 6.71b).

The great majority of galvanizing lines apply a hot dip approach. The low-carbon steel strips and sheets with a thickness range of 0.2 to 4.5 mm and a width range of 0.5 to 1.9 m are typically used in hot dip galvanizing lines. Strip processing speed typically ranges from 7.6 to 200 m/min. The coating thickness is controlled by the speed of the strip and the “air knife” wiping system. The air knife is located just above the zinc melting pot representing a complex apparatus (Figure 6.72a). Air, steam, or nitrogen can be used as the wiping medium. The air knife blows the excessive amount of coating alloy off the strip surface down into the melting pot before the coating is solidified.

IH can also be applied in the post-coat heat treatment of the strip. Suppliers around the world use various names and trademarks to describe a post-coat heat treatment, but in essence, it is commonly described as Galvanneal or Zincanneal. In the present text, this process is referred to as galvannealing. Galvannealing involves heating the coated strip that passes from the zinc melting point (approximately 420°C) to temperatures in the 500°C to 580°C range, holding/soaking at that temperature for a specified period, and then cooling the strip down for additional treatment.

Depending on the requirements of a particular process, instead of pure zinc, the binary zinc–aluminum alloys or ternary alloys are also used as a coating material. Numerous recipes of metal coatings and trademarks have resulted in various coatings used in hot dip coating processes (e.g., Galfan, Galvalume, Alusi, Alupur, Galflex, etc.).

When coating with Zn–Al alloy, the aluminum adheres to the steel strip first and provides an alloy layer that inhibits the migration of iron into the zinc. This latter is a time-driven action requiring a certain length of the holding (soaking) zone. This action depends on the local concentration gradient of the iron in the zinc layer.

A uniform temperature distribution across the strip width during the holding (soaking) stage is critical for obtaining the required quality of coated strip. Normally, the strip has a uniform transverse temperature profile after exiting a molten zinc pot. However, because of the specifics of air/gas flow resulting from operation of the air knife, the strip edges have a tendency to be cooler compared to the central part of the strip before entering an induction postheating system and holding zone. This phenomenon of edge heat deficit should be compensated for when choosing the design parameters of the induction postheater.
Induction Mass Heating

The strip cooling after exiting a holding/soaking zone also plays an important role in obtaining the required structure of the coating layer since, upon cooling, the zinc layer “freezes” into a different lattice structure. After solidification of the metal coating, the hard coating can come into contact with guiding rollers without developing marks at the strip surface and producing a uniform matte gray zinc finish suitable for fabrication and offering improved weldability and paintability compared to galvanized strips.

IH can be used not only for induction strip preheating and postheating but also for the holding chambers, which are designed to be moved on and off the line as required. Figure 6.73 shows a sketch of a strip galvannealing line.

Conventional solenoid coils, inductors with “doors,” and doorless coils that provide a side opening are available for this operation. Figure 6.72b shows a strip galvannealing line that consists of a pot of molten zinc alloy and induction strip reheater utilizing two doorless inductors, and holding zone. Frequencies of 30 to 120 kHz are the most commonly used for galvannealing applications.

A modern strip processing line is designed to be able to handle a variety of strip sizes. A typical line runs as follows:

- The lightest and widest strip is processed through the line first.
- If there is a need, the same thickness strips at progressively narrower widths are processed next. There is no line speed adjustments required.
- Strips of heavier thickness are processed at decreasing line speeds. For each strip gauge, the widest strips are processed first followed by the narrower strips.
FIGURE 6.73
Sketch of the strip galvannealing line. (Courtesy of Inductotherm-Australia.)
Since roll wear typically occurs at the strip edges, this procedure keeps the good roll surface in contact with the more critical strip geometry. Because heavier thickness strips are typically used for applications that do not demand as critical surface requirements as lighter thickness strips, the thicker strips are processed last. At the end of a run that typically lasts several weeks, the line is shut down and general maintenance such as sink roll change, air knife change, cleaning maintenance, and so on is performed.

Because of the precarious location of heating coils in the vicinity of the molten metal bath, often high in the air, it is necessary to take safety precautions to prevent injury to maintenance workers. Care must also be taken to ensure that no water leakage from coil cooling lines occurs over the molten bath.

In order to optimize transition processes in strip processing lines, induction boost heaters (boosters) have been developed. Figure 4.128 shows a coil used as a booster. The system is installed in the horizontal passline of an L-shaped annealing gas furnace and designed to minimize production losses owing to transitions caused by changing the strip size (i.e., strip gauge) or process cycle.

The long response time of gas furnaces (because of their large thermal mass/thermal inertia) produces a significant amount of scrap when a production transition occurs. Either underheating heavier gauge strips or overheating lighter gauges may cause scrap until a new steady-state cycle is established when strip sizes or thermal protocols are changed.

Induction heaters provide the unique capability of practically instantaneous response to a change in process parameters to reduce this time lag and decrease production loss during the transient time and resulting in higher yields. Because of this seamless transition, a wide variety of strip gauges can be run at the same line speed.

Induction boosters can be placed inside the steel furnace casting being thermally insulated from the surrounding 705°C atmosphere consisting of a mixture of approximately 94% nitrogen and 6% hydrogen. As shown in Figure 4.128, in order to minimize heat losses into the hot atmosphere, the water-cooled inductor is thermally insulated outside as well as inside. The bus connection that carries current from the inverter is sealed gas-tight against atmosphere leakage. Atmosphere leakage is dangerous if leaks are to the outside as the hydrogen can form an explosive mixture if allowed to accumulate. If the leak is formed outside to inside, the air will cause the strip at elevated temperature to oxidize. Since zinc will not adhere to an oxidized strip, this means a loss in production.

This type of induction heater can also be used to increase furnace capacity even when not used for transitions by applying additional energy in order to process more throughput of strip.

Tin plating (tinning) represents another form of metallic coating of carbon steel strips and sheets. Tin-plated strips are used by the food industry [567,586]. The corrosion resistance of tin is much greater than that of carbon steel. Tinning lines accept carbon steel strip from the “double reduced” tinplate or temper mill and process it by welding, cleaning, pickling, plating, reflowing, chemical treating, and coiling or shearing.

The thickness of tin-plated strips typically ranges from 0.1 to 0.9 mm with a maximum strip width of 1.1 m. It has been reported that a maximum speed of some tinning lines can exceed 600 m/min. Tin plating is accomplished as a bonding process because of the electrolytic reaction of electrolysis, with the tin being cathodic to the carbon steel [567,586].

An important part of the process of tin-plating deals with the necessity to remelt (reflow) a tin layer (melting point of tin is approximately 231°C [448°F]). The specific appearance of the strip surface can be achieved by a tin reflow that provides certain visual and aesthetic properties (e.g., a glossy surface). In addition, it provides good bonding between the
coating layer and the base metal (carbon steel). It was also found that dull (not reflowed) tin corrodes at a faster rate than highly polished reflowed tin.

The most long-lasting protection of a carbon steel strip against corrosion can be obtained by applying not only a metallic coating but also a combination of metallic and nonmetallic coatings (organic and inorganic topcoat).

6.9.1.2 Nonmetallic Coatings

Nonmetallic coating and painting provide not only a corrosion-resistant product but it is often desirable for aesthetic and camouflage purposes. Paint/coating lines represent a multizone system where the metallic strip is coated with a variety of coatings that include primers, paints, porcelain, enamels, corrosion-resistant ceramics, epoxies, polymers, and others. In these applications, IH has been used for strip preheating before coating or heating after coating for curing, or a combination of both.

There is a fundamental difference between IH and convection/radiation furnaces used for strip heating in paint/varnish/organic coating lines. The difference lies in the ability of induction to heat internally, beneath the coating, leaving the surface soft and allowing the solvents to evaporate much more rapidly than curing with convection or radiant heating, which heats from the outside in. When heating the outside first, the surface of the coating is cured and hardened, trapping the solvents between the substrate and the coating skin, making it far more difficult and time consuming for the solvent to evaporate from the coating. Because electromagnetic induction heats the substrate inside-out, there are no pinholes in the coating.

The process specifics dictates the heating requirements and, in general, the required temperatures are relatively low (i.e., from 50°C to 280°C), but the temperature uniformity is very tight and critical. Frequencies of 6 to 30 kHz are typically used. The organic coating processes consist of solvent-based wet paints, water-based wet paints, and dry powder coatings. Some organic coatings may contain corrosion inhibitors that provide additional suppression of corrosion.

6.9.2 Coil Design Concepts for Heating Strips, Plates, Sheets, and Thin Slabs

There are several basic coil designs for heating workpieces of these general shapes [78–80]:

1. Longitudinal flux inductors (solenoid coils)
2. Transverse flux inductors
3. Traveling wave inductors
4. Channel-type coils
5. C-core inductors

Generally speaking, these designs are distinguished by the orientation of the main magnetic flux with respect to the heated workpiece and inductor geometry. Each design has certain advantages and all have been used either alone or in combination with others.

Unlike of IH of slabs or thick plates, skin effect does not typically cause a significant surface-to-core temperature nonuniformity in strip heating, because the thermal conductivity is able to quickly equalize the temperature within the strip thickness (unless extremely short heat times are used).
Therefore, when designing continuous strip heating lines, the major concern is the ability to provide temperature uniformity across the strip width, which is primarily affected by a distortion of the EMF in the edge areas and proximity effect.

No single type of coil will provide acceptable heating results in all strip-heating applications. Therefore, the selection of the most appropriate inductor design relies on specifics of the application.

### 6.9.2.1 Longitudinal Flux Inductor (Solenoid Coil)

A longitudinal flux inductor can be described as a solenoid induction heater (Figure 6.74) similar to that used in the IH of slabs. Traditionally, these heaters have high $\eta_{el}$ and reduced sensitivity to strip-to-coil positioning and provide sufficient heat uniformity across the strip width. As in the case of IH of slabs, high coil electrical efficiency will be obtained if the ratio of strip thickness $d$ to penetration depth $\delta$ is 2.5 or greater. The optimal value of the frequency that corresponds to the maximum coil efficiency can be estimated by using Equations 6.10 and 6.11.

The use of a frequency higher than those values will only marginally change the coil electrical efficiency. However, the use of frequencies higher than optimal might be a preferable choice in cases when it is necessary to have higher heating intensity in the strip edges of a thick strip compared to its central part (Figure 4.215). This is typically the case with strip reheating when the strip’s edges have a lower initial temperature than its central part.

Note that sometimes the strip thickness is not the same across the strip width and depends on a previous rolling process. In cases like this, an appropriate frequency might be different from a recommendation that is based on the assumption of uniform thickness.

It should also be noted that the frequency that corresponds to the maximum of $\eta_{el}$ might not produce the most uniform heating.

If the chosen frequency is noticeably lower than the optimal value, the coil efficiency will dramatically decrease owing to cancellation of the induced currents circulating in the opposite sides of the strip.

Longitudinal flux inductors are normally less demanding with respect to having a tight coil-to-strip gap, less sensitive to strip positioning within the induction coil, and usually do not require time-consuming adjustments for heating strips with different widths and thicknesses. These types of inductors are particularly energy efficient when used for heating of ferromagnetic strips when the final temperature is below the Curie point. A dual-frequency approach discussed earlier is also useful for heating strips above the Curie temperature.

**FIGURE 6.74**

Longitudinal flux inductors for heating strips are similar to solenoid induction heaters that are used in the heating of slabs.
Solenoid inductors are used for heating nonmagnetic low-resistivity (e.g., aluminum, copper, brass, etc.) thin slabs, plates, and thick strips as well.

The process of IH of magnetic thin strips from room temperature, or a temperature below the Curie point, to a temperature above it has several features that could call for special design. At the beginning of the heating cycle (the initial stage), the whole strip is ferromagnetic and the process of heating is very efficient when using a longitudinal flux inductor assuming that the frequency has been properly selected. After the strip temperature approaches the Curie point, the heat intensity will significantly decrease and IH might become inefficient. To avoid this, one could use not only a dual-frequency but also a dual-inductor approach. According to this approach, a solenoid-type inductor can be used for IH of the strip to the temperatures just below the Curie point. In the second stage when the thin carbon steel becomes nonmagnetic, it may be more efficient to use an alternative inductor style, for example, a transverse flux inductor or traveling wave inductor, which will be discussed in the following sections.

It is important to keep in mind that the above-discussed formulas allow one to determine the suitable frequency that corresponds to the maximum coil electrical efficiency when heating uncoated strips or strips with a nonelectrically conductive coating (e.g., paint). At the same time, in many cases, it is required to heat strips that have a metallic coating (Figure 6.75), for example, IH a carbon steel (being the base metal) that has zinc–aluminum or copper alloy coating. If the thickness of the metallic coating is comparable to the \( \delta \) in the coating alloy \( (d_{\text{coating}}/\delta_{\text{coating}} \geq 1.5) \), then, electromagnetically speaking, regardless of the existence of the base metal, the magnetic field will “see” only the metallic coating (Figure 6.76) and the presence of the base metal will be taken into consideration only in thermal calculation when determining the required power.

If the thickness of the metallic coating is less than 5% of \( \delta \), then the metallic coating will be transparent to the magnetic field (practically speaking). The magnetic field will “see” the base metal only. In this case, the existence of the coating may be taken into consideration only in thermal calculations.

![FIGURE 6.75](image1.png)

**FIGURE 6.75**
Sketch of transverse cross section of a metal coated strip.

![FIGURE 6.76](image2.png)

**FIGURE 6.76**
Eddy current flow within top half of the transverse cross section of the metal-coated strip when the thickness of the metal coating is comparable to the current penetration depth in the coating alloy.
In the ratio $1.5 \geq \frac{d_{\text{coating}}}{\delta_{\text{coating}}} \geq 0.05$, there will be a complex distribution of induced eddy current along the strip thickness dealing with the dual-property phenomenon, which may produce a wave-shape profile that is different from the classical exponential distribution and similar to the phenomenon discussed in Sections 3.3.2 (Figure 3.54) and 4.2.2.4 (Figure 4.89).

It would be beneficial to emphasize once again that, in the case of using longitudinal flux inductors, the temperature uniformity across the strip width depends on several factors, one of which is the frequency. Very low frequency results in underheated edges. In contrast, too high a frequency results in heat surplus there. There is a range of frequencies that can produce a reasonably uniform transverse temperature distribution. At this point, it would be beneficial to clarify what it meant by “too low a frequency” and “too high a frequency.”

For example, is a frequency of 10 kHz a high frequency or a low one? As one can conclude from the discussion in Section 3.1.2, this is not the correct question. A frequency of 10 kHz may be considered as a high frequency in some strip-heating applications, and in others, it may be considered as a very low frequency. Whether a frequency is too high or too low depends on the ratio of strip thickness to current penetration depth ($d/\delta$). If this ratio is less than 1.6, the frequency is too low, resulting in poor coil efficiency and may also be associated with appreciable edge underheating. If the ratio is 20 or higher, then the frequency is considered to be high, resulting in high coil efficiency but, at the same time, might lead to overheated edges as well as potentially high equipment cost. The most appropriate frequencies for strip-heating applications typically result in a $d/\delta$ ratio of 3 to 12.

Another factor that can affect the transverse temperature profile is the shape of the strip (its “out-of-flatness”) inside the induction coil (Figure 6.77) and whether the coil is electromagnetically long or short. If the strip is not symmetrically positioned while it progresses through a multicoil induction line, the transverse temperature nonuniformity can be amplified. If the induction coil is electromagnetically short or consists of a number of electromagnetically short sections or banks, then such a coil might be more sensitive to variation of the strip positioning and geometry. Making electromagnetically long coils/sections can help decrease the sensitivity of heating to the strip out-of-flatness and its positioning. The use of magnetic flux concentrators is a step toward transforming electromagnetically short coils to electromagnetically long coils without actually changing the coil geometry.

The third factor that affects transverse temperature uniformity is inconsistent strip thickness. It is particularly critical when processing thin gauge strips having nonuniform transverse thickness profiles. Quite often, strip-processing companies have several strip suppliers. Every mill can supply a strip in the range of width and thickness but may have

![FIGURE 6.77](Variety of shapes of the strip inside an induction coil.)
different capabilities to hold the strip thickness uniformity. The thickness variation across the strip width can affect the temperature profile in two ways:

- Thinner areas will have a smaller mass of metal; therefore, those areas can be heated to higher temperatures compared to thicker areas, resulting in local temperature nonuniformities. This phenomenon is frequency independent.
- A second phenomenon typically takes place only in cases when the chosen frequency results in a \( d/\delta \) ratio of less than 2.6. In this case, dramatic eddy current cancellation can take place in thin areas of the strip.

Therefore, on one hand, the thin areas have a lesser amount of metal to be heated, resulting in a tendency to produce hot spots. On the other hand, the occurrence of severe eddy current cancellation in those areas can lead to the appearance of cold spots. The final thermal condition in thin areas of the strip depends on the impact of both factors.

An additional factor that can affect the temperature distribution across the strip width is related to metallic coatings. Coating thickness may vary across the strip width and, under certain conditions, can lead to a nonuniform transverse temperature distribution. The coating thickness can vary in several ways, including

1. Different sides of the strip could have uniform but different thickness
2. The coating thickness can vary from edge to edge of the strip
3. The coating thickness is generally uniform; however, there are some localized areas (patches) that have different coating thicknesses

Among the design criteria that are typical for all IH systems, there are some specific design considerations for strip-coating applications. This includes the necessity of avoiding the vibration marks or a unique form of striping (striation) phenomenon. This phenomenon manifests itself in the appearance of the coating marks at strip surface.

There are several different types of striping phenomena. Section 4.2.8.1 discussed several types of striping phenomena. Stripes/striations appearing in strip-coating applications such as galvanizing and tin reflow are typically longitudinally oriented (Figure 6.78).

Shortly after the heating begins, alternating bright and dark areas on the strip surface become visible. These bright and dark stripes are somewhat similar to standing waves. In some applications, striping suddenly occurs, and in others, it disappears. One of the possible explanations of this phenomenon has been published in Ref. [588] and is related to elastic buckling of the strip. This buckling takes place because of a complex distribution of the magnetic forces (magnetic pressure) acting on the strip (Figure 6.78a). Forces that provide pulsating magnetic pressure on the strip edges in the direction where thin strips have little stiffness result in elastic buckling of the strip (Figure 6.78b).

It has been found that the appearance of coating marks depends on a complex function of frequency, strip width and thickness, power density, type and thickness of the coating, strip flatness, tension, and its natural mechanical vibration frequency. As one can see, this phenomenon has a complex nature associated with mechanical vibration (the mechanical standing waves) and electrodynamics. The experience of successful designs allows a manufacturer of induction strip heating lines to build an inherently stripe-free process. As an example, Ref. [588] suggests the formula for an approximate estimation of the buckling mechanism applied to a steel strip.
Induction Mass Heating

One of the challenges in induction strip heating design is caused by the geometry variation of the products (i.e., strip thickness or width) that are heated in the same coil. However, the problem of providing a uniform transverse temperature distribution is not nearly as challenging with a longitudinal flux inductor as with alternative styles (i.e., transverse flux or traveling wave inductors).

### 6.9.2.2 Transverse Flux Induction Heater

The transverse flux inductor is one of the oldest IH techniques, having been developed for use in the aluminum alloy strip heating industry in the early 1940s. The principles of the process, analytical simulation subroutines, and case studies of industrial utilization of transverse flux induction heaters (TFIHs) were reported by R. M. Baker and M. Lamouredieu as early as 1950 [593–596]. This process was established as a way to overcome the eddy current cancellation problem of IH of thin nonmagnetic strips and films when using solenoid (longitudinal flux) inductors.

In the conventional TFIH, the strip passes through inductor pairs that are located on both sides of the strip, as shown in Figure 6.79. These coil pairs create a common magnetic flux. Unlike the longitudinal flux inductor, in the TFIH, the eddy currents complete their path within the plane of the strip and not just within the strip thickness. This allows IH of a thin strip to be carried out with high power densities using relatively low frequencies.

**FIGURE 6.78**
Striping phenomena in IH of coated strip. (a) Electromagnetic forces acting on the strip. (b) Elastic buckling of the strip due to magnetic pressure. (c) Longitudinal appearance of “striping” phenomenon.
TFIH systems typically require less floor space compared to solenoid coils and frequently apply magnetic flux concentrators.

Electrically efficient heating can be obtained when the coil-to-strip air gap is relatively small and the strip thickness is 1.5 to 2 times the $\delta$ or less. Without satisfying the latter condition, the transverse flux effect may disappear and conventional proximity heating will take place. Proximity heating is known for having lower $\eta_{el}$ compared to longitudinal flux and, in particular, transverse flux heating.

The greatest challenge in utilizing TFIH is associated with obtaining temperature uniformity across the strip width. The heat time of TFIH is typically quite short, ranging from a fraction of a second to several seconds; therefore, the thermal conductivity does not have much of a chance to equalize the temperature gradients across the strip width.

The eddy current paths in the strip match the shape of the transverse flux inductors. Therefore, if TFIH is sufficiently wide, the induced current reaches the edge of the strip and then it can only continue to flow along the strip edge (Figure 6.80a). Because of this natural phenomenon, in cases where coil width is greater than the width of the strip, the energy generation in the strip edge area will be greater compared to the strip central area and, as a result, the strip edges may have measurable heat surplus. However, if the transverse inductor is narrower compared to the strip width, then the strip edge areas will be
underheated because the eddy current will not reach the strip edges. Obviously, somewhere between these extreme cases, there is a condition for reasonably uniform heating. Figure 6.80b shows three of the most typical temperature profiles across the strip width.

In addition to the electromagnetic properties of the heated metal and strip-to-inductor geometry, there are four other factors that have a major impact on the electrical parameters of TFIH greatly affecting its temperature distribution across the strip width:

- Pole step (pole pitch)
- Pole length
- Coil opening
- Frequency

Over the last four decades, different complex-shaped transverse flux inductors have appeared quite regularly [593–603]. This includes diamond-shaped coils, J- and O-type coils, pairs of U-shaped coils (Figure 6.81), and many others. In some cases, as an attempt to provide the required temperature uniformity, the poles of the TFIH were deliberately shifted (Figure 6.82).

Theoretically speaking, some of the TFIH inductors were suitable for a broad production mix and immune to unstable strip positioning. However, in practice, most of these inductors have considerable limitations in providing the required temperature repeatability and uniformity across the strip width when the strip width and thickness vary substantially or when the strip moves left to right or up and down inside the transverse flux inductor.

One of the possible solutions for designing a TFIH line that would be less sensitive to strip movement in the transverse direction would be to build moveable inductors, which
could trace the strip movement. However, this approach drastically increases the capital cost of the TFIH, requiring a cumbersome control system.

One of the most practical uses of the TFIH and its ability to generate the heat surplus in edge areas is the edge reheating of plates, strips, slabs, and transfer bars. In applications such as these, the natural tendency of wide TFIH to overheat edges that is typically considered as an undesirable effect can work advantageously. A properly designed TFIH allows one to obtain high coil electrical efficiency of edge reheaters in the range of 65% to 75% in combination with the inductor’s ability to produce repeatable temperature profiles that would not be very sensitive to variation of the strip, slab, or transfer bar width and thickness.

New developments in advanced high-strength sheet steels (AHSS) intensity R&D activities in designing novel TFIH.

6.9.2.3 Traveling Wave Induction Heater

The traveling wave inductors are not as commonly used for strip-heating applications as TFIH or particularly longitudinal flux inductors. The main reasons for this are the complexity and sensitivity of the process and the fact that there has not been enough experimental and research work done in developing a traveling wave induction heater (TWIH).

The fundamental concept of this process is quite simple and is similar to that of the conventional three-phase linear induction motor where the strip takes the place of the rotor and the inductor can be considered a stator (Figure 6.83). The inductor turns are located quite close to each other and carry multiphase currents. The turns are located in the slots of a flux concentrator (e.g., laminated low-carbon steel packs). The inverse connections of the middle phases have been used to reduce current cancellation in neighboring turns.

The three-phase or two-phase current flows through the inductor turns, producing traveling wave EMF and generating heat sources in the strip. One of the main advantages of a traveling wave system is its low level of vibration and industrial noise compared to TFIH. This feature might be particularly important when IH nonmagnetic (aluminum, copper, etc) thin strips.

EMF plays a major role in the appearance of industrial noise. As has been shown in Ref. [604], when applying TWIH, there is only a static component of magnetic force and not a dynamic component (a dynamic component is a function of the frequency and is the major source of vibration and noise). Therefore, the major source of vibration associated with TFIH is eliminated when using traveling wave inductors, making these inductors quieter compared to TFIH and allowing one to prevent the “sucking” action when the strip is suddenly “sucked” toward one of the sides of the inductor, which sometimes takes place with TFIH (in cases where the tension force is not sufficient to stabilize the strip in the middle of the coil).

![FIGURE 6.83](image_url)

*Traveling wave induction heater.*
An important feature of TWIH deals with the fact that an electromagnetic traveling wave creates an EMF oriented in the direction of the strip travel (longitudinal direction). This force provides an additional tension, which can coincide with the applied tension or be opposite to it (depending on phase switching). This helps stabilize strip positioning inside the inductor.

Besides the described advantages, a TWIH has some limitations that prevent wider use of this technology. A common shortcoming of both TFIH and the TWIH deals with the fact that in order to have high electrical efficiency, small air gaps between the coil copper and strip are required. This often leads to difficulties with respect to strip processing and mechanical design.

Another shortcoming of TWIH deals with the fact that regardless of the use of magnetic flux concentrators and because of the closeness of multiphase turns, there is magnetic coupling between the turns carrying currents with different phases. This produces some magnetic field cancellation in adjacent sections, leading to a reduction of the total electrical efficiency of the TWIH compared to the TFIH.

Finally, there is still the challenge of obtaining a uniform temperature profile across the width for different strip gauges and width variations or requiring numerous sets of TWIH coils that accommodate only certain strip geometries.

### 6.9.2.4 Channel-Type Edge Heaters

Among a variety of applications requiring IH of thin slabs, plates, and strips, there are applications that do not require heating the whole workpiece but only certain selected areas. Induction reheating of edge areas of continuously cast thin slabs is one example where selective induction reheating is required. There are several approaches to reheating edges of a rectangular workpiece, including the following:

- **Solenoid longitudinal flux coils** applying higher frequencies than required for uniform heating. Because of the electromagnetic transverse edge effect, the edge areas may be heated at a greater rate than the central area.

- **Transverse flux and traveling wave heaters** can also be used to reheat edges. As discussed above, edge overheating is a major concern when utilizing these types of inductors. Therefore, in cases where edge areas initially have a lower temperature than the rest of the workpiece and where it is primarily required to reheat edge areas, this disadvantage can be turned into an advantage since both approaches (TFIH and TWIH) have a tendency to generate more heat in the edge areas compared to the rest of the workpiece.

- **Utilization of channel-type inductors** creates another possibility for providing selective heating of the edge areas.

A channel-type inductor is a tunnel-shaped coil that is similar to the channel inductors discussed in the heat treating (Figure 6.84). The workpiece areas located under the inductors will be heated, because of the proximity effect. These inductors have not been widely used for strip-heating applications but rather for IH of thin slabs and plates.

The main advantage of the channel-type inductor is the ease of entry and exit for the workpiece. Flux concentrators are often used to increase its electrical efficiency and concentrate the magnetic field in the area required to be heated. Flux concentrators also help reduce the EMF exposure.
The efficiency of a channel inductor is quite sensitive to the air gap between the coil and slab. If there are significant variations in slab width, one or both of the channel coils can be made flexible enough that the channel inductors can be moved in and out and adjusted to the workpiece geometry. This keeps the induction heater efficient and allows various edge heating patterns for different production mixes.

### 6.9.2.5 C-Core Edge Heaters

The C-core induction edge heater is an alternative for applying the above-discussed induction edge heating of thin slabs, plates, flat bars and thick strips. This type of inductor was discussed in Section 4.6.3.3 in applications for induction tempering. Therefore, its coverage here is limited.

One or several induction coils are wound around the core to create a common magnetic flux (Figure 6.85). Slabs or plates are passed through the opening (air gap) of the C-core transformer. Eddy currents are mainly induced in the edge areas of the slab or plate. As a result, intense heating of the slab or plate edges takes place.

The efficiency of this type of induction heater depends greatly on the air gap and material properties of the slab. The mechanical design of an adjustable inductor is obviously not an easy one and is quite expensive. In some cases, the strip can be sucked in to a side of the C-core inductor.

When heating nonmagnetic strips (steel heated above the Curie point such as applications in hot strip mills), additional challenges appear when using this type of inductor. However, several industrial installations have been built with adjustable C-core slab/flat bar in-line edge heaters before the finishing mill to compensate for edge cooling after the rough mill operation [616–618]. Slab/strip thickness is typically within the 25- to 40-mm range. Line speed is 0.8–1.2 m/s. The required temperature rise is 50°C–70°C at a nominal
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temperature level of 1000°C–1070°C. The edge area required to be heated is usually within 20–40 mm from each edge.

Challenges associated with this technology include but are not limited to the following:

- It is not unusual that distortion of incoming flat workpieces exceeds expected tolerances; thus, measures should be taken to prevent inductor damage from accidental impact. Equipment should be able to safely retract before the damage is done.
- Certain adjustability of upper and lower coils are required, which not only makes this system expensive but also raises the possibility of having “hot” spots as a result of localized high concentration of magnetic flux.
- Since this technology calls for using low frequencies (50–400 Hz, with 300 Hz being more typical) at powers of 750–1250 kW per single unit, it is known to be quite noisy. The source of noise generation not only is caused by strip vibration but also is associated with vibration of components of the induction system due to significant magnetic forces.
- Laminated iron cores cannot be exposed to such high working temperatures that would result in their deterioration. Thus, specifically designed thermal refractory structures must be applied to protect the heating faces of C-core inductors from excessive heat radiation and to provide the needed protection from scale buildup and erosion without greatly reducing heating efficiency.

6.9.2.6 Doorless Technology for Strip Processing Lines

The ability to move the induction coil from the heating position to an offline position is an important system requirement in such strip-coating applications as galvannealing. Before 1995, these systems commonly used a solenoid coil having a “door” with electrical contacts [619] that, when closed, conducted the full coil current (Figure 6.86a). This coil with a door is actually a split coil (which is also referred to as a clamshell inductor) that has been used in induction hardening since the 1960s (Figure 4.101a) [7].

A good surface-to-surface contact has to be maintained between the faces of the movable part of the split inductor that is called the hinge or door. Insufficient contact results in failure due to current concentration within the areas of local contacts, overheating, and the appearance of arcs, burns, and contact wear (Section 4.2.3.5).

Contact faces are polished and silver alloy coated as an attempt to improve coil life. In addition, substantial clamping pressure is applied to further improve the reliability of the contact. Unfortunately, contamination is always present in a real-life production environment of coating operations and quickly builds up on contact surfaces, increasing transient electrical resistance between contact surfaces and causing well-known difficulties related to premature failure, particularly when using high frequencies and high voltages.

The patented doorless inductor [620,621] was developed to increase coil life, significantly simplify maintenance, and improve reliability compared to inductors with doors. Solenoid coils, which provide uniform heating and are very efficient, are often the preferable choice in the majority of strip-heating applications. The doorless inductor is a clever adaptation of this existing proven technology. A doorless coil is obtained by using two coils connected electrically in series and rotating the interconnection bus such that one coil is over the other. As shown in Figure 6.86b, from an electromagnetic perspective, a doorless inductor consists of two solenoid coils connected in series with the strip passing through them for
heating to the needed temperatures. The gap between the interconnecting bus and coils allows passage of the strip without the necessity of having a door.

Removal of the door eliminates the need to make and break electrical connections each time the IH unit is moved offline. With the elimination of these high-current–carrying electrical connections, reliability is increased dramatically with significantly improved maintainability. To move the coil offline, air cylinders are used on each side of the interconnection bus to slightly spring it 65 mm in each direction, providing a 125-mm-gap that is typically sufficient for strip to pass through. However, if necessary, this doorless coil can easily provide a much greater opening.

This patented doorless inductor technology eliminates the need to provide an electrical contact along areas that can be as long as 1 m in a split coil with a door.

The doorless inductor is made from wide sheets of copper and consists of a nonferrous support frame and outer panels sealed with gaskets. The whole assembly can be connected to a dry air source for pressurization to completely eliminate zinc dust from the coil. Depending on the application, the inductor may have an inner refractory liner.

From an electromagnetic perspective, the strip is heated in a doorless inductor in a manner practically identical to using a highly efficient conventional solenoid coil; therefore, the efficiency of the doorless inductor is as high as the efficiency of a conventional solenoid-type coil.
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Power Supplies for Modern Induction Heating

Induction heating (IH) power supplies are frequency changers that convert power at the available utility line frequency to single-phase power at a frequency appropriate for the particular IH application. They are often referred to as converters, inverters, or oscillators, but they are generally a combination of these. The converter portion of the power supply converts the line frequency alternating current (AC) input to direct current (DC), and the inverter or oscillator portion changes the DC to single-phase AC at the required heating frequency.

7.1 Power–Frequency Combinations

Many different power supply types and models are available to meet the heating requirements of a nearly endless variety of IH applications (Figure 7.1) [626–631,647].

The specific application will dictate the frequency, power level, and other inductor parameters such as coil voltage, current, and power factor or Q. Figure 7.2 illustrates this power versus frequency relationship for common induction heat-treating applications. Figure 7.3 illustrates this same relationship for IH before metal hot and warm working operations.

Frequency is a very important parameter because it is the primary control over the depth of current penetration as discussed in detail in Section 3.1. Frequency is also important in the design of power supplies because the power components must be rated for operation at the specified frequency. The power circuit must ensure that these components are operated with an adequate margin to yield high reliability at the selected frequency.

7.2 Elements of Power Electronics

To gain a fundamental understanding of the various IH power supply circuits, it is first necessary to know the function of the basic power electronic components that are commonly used. These components include resistors, inductors, capacitors, transformers, and power semiconductors.

For those with little or no knowledge of electronics, a mechanical analogy may be helpful. Resistance is like friction in that it dissipates energy and generates heat. Inductance is like the inertia of a flywheel as it stores energy and opposes change. Capacitance is like a mechanical spring that stores energy while promoting change. When inductors, capacitors, and resistors are connected as shown in Figure 7.4a, a resonant circuit is formed, which tends to oscillate at a single frequency determined by the value of the components.
FIGURE 7.1
Different power supply types and models are available to meet the heating requirements of a nearly endless variety of induction applications. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)

FIGURE 7.2
Power–frequency diagram for typical induction heat-treating applications.

FIGURE 7.3
Power–frequency diagram for typical IH before metal forming operations.
In a similar manner, when a flywheel mounted on a shaft with a bearing is mechanically connected to a spring as illustrated in Figure 7.4b, it will also oscillate at a natural resonant frequency. The frequency of this oscillation is determined by the size of the flywheel and the spring. The friction of the bearing on the shaft will damp the oscillation and in the process produce heat, just as the resistance in the electrical circuit damps the oscillation and in the process develops heat.

A mechanical analogy can also be used to explain the function of a transformer as illustrated in Figure 7.5. In a mechanical system, a gearbox is used to match the speed and torque requirements of two portions of the system. In an electrical system, a transformer is used to match the impedance of two portions of a circuit. This means that a transformer can reduce voltage and increase current or alternately increase voltage and decrease current while maintaining the same volt amp product on both the input and output sides of the transformer.

### 7.2.1 Inductors
Most modern IH power supplies are of the “load resonant” type. This means that the inductive and resistive portion of the power supply circuit is actually provided by the heating coil and the resistance of the workpiece being induction heated. The geometry of this coil, which is usually dictated by the application specifics, determines the value of circuit inductance and resistance. The specific design and resulting parameters of various IH coils are covered in detail in Chapters 4, 5, and 6.
7.2.2 Capacitors

Power capacitors used in IH equipment must be capable of withstanding high voltage while carrying high current at the IH frequency. These capacitors come in a variety of sizes and shapes as shown in Figure 7.6. Most are water cooled and packaged in an aluminum case with large studs for power connection to bus bars. It is important that these capacitors be designed to have very low values of internal resistance and inductance to minimize power loss and voltage drop within the capacitor.

7.2.3 Litz Wire and Cable

Losses attributed to high-frequency skin effect and proximity effect in cables used within and to interconnect power supplies are minimized through the use of Litz cable. This cable is constructed using individual insulated strands of copper wire that are small relative to $\delta_{\text{Cu}}$ in copper at its rated frequency. These strands are then bundled and twisted in a manner that further minimizes losses due to both proximity and skin effect. The goal of this construction is to cause each individual strand to occupy positions within the cable that are equal to all the other strands. In this way, current is evenly distributed within each strand so that it carries the same level of current as every other strand [615,632].

7.2.4 Vacuum Tubes and Power Semiconductors

Very early power supplies used high-power vacuum tubes in an oscillator circuit to generate the radio frequency that was used for IH. Modern power supplies utilize power semiconductors such as SCRs, diodes, and transistors to switch the direction of current flow from a direct current source to produce alternating current at a frequency suitable for a particular application. A simple explanation of what these power semiconductors do might be helpful for readers with little or no electronics background. These devices (often referred to by their initials) are switches that open and close to control electric current much the same as a gate or door controls passage from one area to another.

7.2.4.1 SCR or Thyristor

The SCR (silicon controlled rectifier) or thyristor is like a gate with a simple latch that will only swing one way to open. If the gate is pushed in the opening direction and the latch is
not released, the gate remains closed and passage through it is not allowed. This is like an SCR when it is “OFF” or, in electronic terms, forward blocking. As soon as the gatekeeper releases the latch, the gate swings open, allowing passage through to the other side. This is like the SCR when it receives a trigger pulse from the control circuitry and begins to turn “ON” and conducts current. If the people at the gate turn around and begin to push on the other side of the gate, it swings closed and latches, thus preventing passage in either direction. When the voltage reverses on an SCR, it turns off and blocks current flow in the forward direction as well as the reverse direction. The symbol of the SCR and its waveshapes are shown in Figure 7.7.

### 7.2.4.2 Diode or Rectifier

The diode is the simplest power semiconductor. It is like a gate without a latch that only swings open one way. If pushed in one direction, it opens, allowing passage in that direction. If pushed in the opposite direction, it swings closed, preventing passage in the reverse direction. When voltage is applied to a diode in the forward direction, it will conduct current. When the voltage is reversed, the diode begins to block the flow of current. The symbol of the diode and its waveshapes are shown in Figure 7.8.

### 7.2.4.3 Transistors

Transistors are a bit more complicated. They are like a one-way gate that is opened and closed by a gatekeeper. Imagine the gate to be actuated by a hydraulic cylinder controlled by a small valve that is easily switched by the gatekeeper. The small amount of force required by the gatekeeper to control the force of people pushing to get through the gate is like the electronic gain of the transistor. The force with which the people push against the closed gate is like the voltage applied to the transistor. The size of the gate opening limits the rate at which people can pass through to the other side, just as the size of the transistor limits the maximum current it can conduct.

For a transistor to be useful in an IH application, it must (1) block high voltage, (2) carry high current, and (3) switch ON and OFF very quickly. In terms of the above analogy,
the gate must be (1) strong, (2) large in opening, and (3) still be able to open and close very quickly. To build a gate with one or two of these requirements is not a problem. To provide all three in one design is quite difficult. Large strong gates are difficult to open and close quickly. Large gates that move quickly must be light and are therefore not strong, and so on. The symbol and waveshapes for transistors are shown in Figure 7.9.

a. MOSFET. The MOSFET (metal oxide silicon field effect transistor) technology has provided one solution to this problem: a power transistor with relatively high voltage, high current, and very fast switching speeds. This is accomplished by placing thousands of very small, fast transistors that are all connected in parallel on a single chip of silicon, measuring approximately 6 mm (1/4 in.) on a side. As in the analogy, this is like having many small, strong, and rapid gates placed side by side to provide a wide section that can be quickly opened and closed. Larger MOSFET transistor modules combine many of these chips connected in parallel on a common mounting base.

b. IGBT. In the IGBT (insulated gate bipolar transistor), two transistor technologies are combined to obtain high voltage, high current, and fast switching speeds.
Bipolar transistors capable of handling relatively high voltage and high current have been available since about 1970, but they are slow switching and require relatively high-power control signals. Small low-power MOSFET transistors with very fast switching speed and low-power control requirements have also been around for many years. Put the two technologies together with the MOSFET (insulated gate technology) on the control end and the bipolar on the power handling end and you have the best of both in the IGBT.

Figure 7.10 shows a dual 300 amp IGBT module (top left) and a dual 50 amp MOSFET module (top right). Below each is a sample of the same module type with the cover removed to show the multiple chip construction.

c. Transistor Assemblies for More Power. To obtain the high power usually required for IH, many transistor modules are often connected on a single heat sink as shown in Figure 7.11.

The inverter circuits that convert DC to AC use solid-state switching devices such as thyristors (SCRs) and transistors. For high power and lower frequencies, large thyristors are commonly used. For frequencies above 10 kHz or for low power, transistors are
used because of their ability to be turned on and off very quickly with low switching losses.

7.2.4.4 Vacuum Tube Oscillators

Vacuum tube oscillators have been used extensively for many years at frequencies above 300 kHz. However, the tube oscillator has a low conversion efficiency of typically 50% to 60% compared to 83% to 95% for an inverter using transistors. Power vacuum tubes have a useful life of 2000 to 4000 h and are therefore a costly maintenance item. The high voltage (over 10,000 V) required for tube operation is more dangerous than the 1000 V or less present in typical transistorized inverters. These negative features of the tube oscillator have brought about a dramatic move toward the use of transistorized power supplies in most heat treatment applications that require a frequency of less than 1 MHz.

7.2.4.5 Power–Frequency Application of Semiconductors

Figure 7.12 shows in graphical form the various power and frequency combinations that are covered by power supplies using different semiconductor technologies. There are obviously large areas of overlap where more than one type of power supply can be used.

7.3 Types of IH Power Supplies

The power required for a given application depends on the volume and kind of material to be heated, the rate of heating, and the efficiency of the heating process. Small areas heated to a shallow depth may require as little as 1 or 2 kW, whereas heating large slabs or wide fast-moving steel strips may require many megawatts of heating power. It is, therefore, necessary to define the process and its power requirements by using the numerical computer modeling techniques described in Chapter 3 or by careful extrapolation from similar applications.
The geometry of the workpiece and coil as well as the electromagnetic properties of the material to be heated and production rate determine the specific coil voltage, current, and power factor. Defining these parameters is necessary to ensure that the output of the power supply is capable of matching the requirements of the coil. Most power supply systems have the ability to match a reasonable range of heating coil parameters.

Physical constraints imposed by the environment in which the induction processing is to be done can also play an important part in the selection or application of the power supply. Each type of power supply, described in detail later in this section, has specific advantages that may directly affect its suitability for a particular application.

Floor space, machine design, and plant layout are important factors. For example, in highly automated machines with a number of hardening and tempering stations, the very compact unitized construction of a transistor-based power supply with self-contained load-matching transformer and capacitors is a definite advantage. On the other hand, for installations requiring a long distance between the power supply and the work coil, the heat station or load-matching portion should be separated from the rest of the power supply and located at the work coil.

Many books and technical papers have been written about the detailed design and theory of operation of the various types of IH power supplies [633–638]. Inclusion of such detail here would likely be of little help to those primarily involved only in the selection or use of these power supplies. Therefore, the following paragraphs only categorize the most commonly used power circuit and control combinations. This gives some insight into the advantages and disadvantages of modern IH power supplies, their applications and features.

A very basic block diagram that applies to nearly all IH power supplies is shown in Figure 7.13. The input is generally three-phase 50 or 60 Hz at a voltage between 220 and 575 V. The first block represents the AC-to-DC converter or rectifier. This section may provide a fixed DC voltage, a variable DC voltage, or a variable DC. The second block represents the inverter or oscillator section, which switches the DC to produce a single-phase AC output. The third block represents the load-matching components, which adapt the output of the inverter to the level required by the induction coil. The control section compares the output of the system to the command signal and adjusts the DC output of the converter, the phase or frequency of the inverter, or both to provide the desired heating.

Figure 7.14 shows the principal design features of the inverter configurations most commonly used in IH power supplies. The two major types are the voltage-fed inverter and the current-fed inverter. The chart further subdivides each of these by the DC source (fixed or variable), the mode of inverter control, and the load circuit connection (series or parallel).
7.3.1 Rectifier or Converter Section

All of the power supplies outlined in the chart in Figure 7.14 have a converter section that converts the line frequency AC to DC. Nearly all IH power supplies use one of four basic converters.

7.3.1.1 Full-Bridge Uncontrolled Rectifier

The simplest is the uncontrolled diode rectifier shown schematically with waveshapes in Figure 7.15. The output voltage of this converter is a fixed value of 1.35 times the input line-to-line voltage, and the converter section provides no control of the output. The uncontrolled rectifier must therefore be used with an inverter section capable of regulating the power supply output. The input power factor of this rectifier is very high, being at 0.95. In this case, the current waveshape is not a sine wave and the difference between the input kilovolt-ampere and kilowatt is only attributed to the shape factor of the current waveshape.
7.3.1.2 Phase-Controlled Rectifier

The phase-controlled rectifier has thyristors that can be switched on in a manner that provides control of the DC output relative to the input line voltage. This relatively simple converter can be used to regulate the output power of the inverter by controlling the DC supply voltage. Figure 7.16 shows (a) the schematic, (b) line voltage, (c) DC voltage, (d) phase current, and (e) line current waveshapes. In the phase-control mode, the gating of the thyristors is delayed; therefore, the switching between phases is forced by the angle of delay. Power drops rapidly with an increase of the delay or retard angle. The increase in retard angle also results in a decrease of the input power factor that is in direct proportion to the decrease in DC output voltage. At reduced operating power, the input power factor may be reduced to levels that are not acceptable under modern power quality standards [639]. Another characteristic of the phase control rectifier is necessarily slow control response time that is limited by the frequency of the input line upon which it is acting.

7.3.1.3 Uncontrolled Rectifier followed by Regulator

The third converter type has an uncontrolled rectifier followed by a switch mode regulator as shown in Figure 7.17. The switch mode regulator shown in the diagram is one
of the simplest forms and is called a buck regulator [637]. The level of DC voltage or current at the output is regulated by rapidly switching the pass transistor on and off. A greater ON-time to OFF-time ratio yields a higher output voltage or current. The converter can therefore regulate the output power of the inverter by controlling the supply of direct current or voltage. The input line power factor is the maximum at all power levels, and the response time can be very fast due to the relatively high switching rate of the buck regulator. Therefore, this converter overcomes some of the disadvantages of
the simple controlled rectifier while being more complex, more costly, and slightly less efficient.

All the above converters just discussed draw non-sine wave current from the input AC line. This means that there are harmonics or multiples of the line frequency present in the current waveshape. This harmonic distortion is discussed in more detail in Section 7.3.3.

### 7.3.1.4 Active Three-Phase Rectifiers

The fourth converter is actually a group of converter circuits that employ transistors (usually IGBTs) to reduce the line current harmonic content, improve the input power factor, and control the output DC voltage. This is accomplished by pulse width modulating (PWM) the switching transistors to control when and how much current is passed from the input line to the converter output. Inductors and capacitors provide energy to smooth both the input line current and the output voltage of the converter. A schematic of one such active converter circuit and its waveshapes are shown in Figures 7.18 and 7.19.

**FIGURE 7.18**

**FIGURE 7.19**
7.3.2 Importance of Good Input Line Power Factor

Energy conservation is an important issue and power companies are beginning to change the power distribution regulations in order to raise the minimum limit for power factor. Some countries are now requiring a minimum power factor of \( \cos \theta = 0.92 \) and are soon going to require 0.95. In most cases, a progressive extra charge is imposed, and in some cases, penalties are imposed for operation with input power factors that are below these minimums. This will of course preclude the use of conventional full-bridge controlled rectifiers.

Care must be taken in the measurement of the power factor of IH installations. High-frequency harmonics and magnetic fields may affect some sophisticated electronic instruments used for automatic measurement of the power factor and consequently give erroneous readings. True root mean square (rms) instruments are most likely to provide more accurate results.

The conventional method for correcting the factory input power factor is to provide line frequency capacitor banks across the incoming lines. This practice can cause undesirable results when used on systems that have significant loading by static power converter equipment, which includes IH power supplies. The harmonic distortion produced by the rectifiers can excite resonance between these power factor correction capacitors and other reactive components in the distribution network. The resulting high-frequency currents can exceed the ratings of the capacitors and other parts of the system, causing unexpected damage.

Modern static VAR compensation equipment is available allowing to correct the power factor to near unity while also suppressing undesirable harmonics. This equipment can be effective; however, it is a relatively costly solution. It is usually better to eliminate the source of the poor power factor than to correct for it.

7.3.3 Input Line Harmonics and Their Reduction

The AC-to-DC converters described above cause some distortion of the supply “utility” voltage and current. Whenever current flow in an AC circuit is switched on and off rather than permitted to follow the voltage waveform, high-frequency currents at integer multiples of the power system frequency (harmonics) are generated \([633,640,641]\). Harmonic distortion of the current waveshape can adversely affect supply transformers and other electronic equipment connected to the same line. In most heat treatment situations where the power supply rating is less than 600 kW and the plant power distribution system provides low source impedance or “stiff line,” a 6-pulse rectifier as described above is acceptable. For higher-power systems or where utility requirements require reduced harmonic content, a 12-pulse rectifier, which has a six-phase input and 12 rectifiers, can be used.

The chart in Figure 7.20 compares the input power factor and typical line current harmonics as a percentage of the fundamental for these rectifier configurations \([641]\). As shown in the chart, the fifth and seventh harmonics are nearly eliminated in the 12-pulse case, resulting in a dramatic reduction of the total harmonic distortion of the line current. Use of higher pulse configurations such as 18 or 24 obviously leads to a further reduction but at considerable expense. Employing an active three-phase rectifier as discussed in Section 7.3.1.4 is another means of dramatically reducing harmonic distortion of the input supply.
Power Supplies for Modern Induction Heating

7.3.3.1 Recommended Distortion Limits

The IEEE Standard 519-2014 defines the limits of voltage and current distortion that should be permitted in electric distribution systems [642].

7.3.3.1.1 Voltage Distortion

Unwanted harmonic currents are a concern because they cause losses and voltage distortion. Current of any frequency that is drawn from the power system results in a voltage drop equal to the product of the current and the impedance of the system. System impedance must be limited to prevent the voltage drop from reducing the voltage at the load to unacceptable levels and to limit voltage distortion that can cause problems for other electronic equipment on the same line. Unfortunately, power systems are highly inductive and their impedance to current flow increases with frequency. This means that relatively low-magnitude high-frequency currents can produce significant voltage distortion.

Total harmonic voltage distortion is the ratio of the total line to neutral harmonic voltage to the fundamental line to neutral voltage.

\[ \text{T.H.D.} = \frac{V_H}{V_{L-N}} \]

where \( V_H \) is the rms sum of all harmonics up to the 50th.

7.3.3.1.2 Line Notching

Line notching occurs when two semiconductors with the same polarity in a rectifier are simultaneously conducting. This occurs in the interval when one rectifier is beginning to turn off while the other is turning on, a process known as commutation. The duration of this time is called the commutation interval. The recommended limits for line notching are provided in Table 7.1. Line notching is a concern because it can cause noise problems in electronic computer and control equipment connected to the same distribution line.

7.3.3.1.3 Current Distortion

The line current waveshape typical of 6-pulse rectifiers is shown in Figure 7.15. The current is not drawn from the input line as a sine wave but as the sum of nearly constant current segments that when summed are equal to the current in the DC output of the rectifier.
The total demand distortion TDD is the total harmonic current distortion given by

$$TDD = \frac{I_H}{I_L},$$

where $I_L$ is the maximum demand load current at the fundamental line frequency and $I_H$ is the rms sum of the individual harmonic components up to the 50th. Table 7.2 shows the current distortion limits for general distribution systems as specified by IEEE Standard 519-2014 [642]. It should be noted that the measurement of this current distortion is taken at “the point of common connection” (PCC) where the power enters the user’s facility. Therefore the current measured is the vector sum of current drawn by all equipment operating in the facility.

Line current harmonics are a concern because they lead to voltage distortion that can adversely affect other equipment on the same distribution circuit. Unwanted additional power losses can also be attributed to line current harmonics. Any components that must conduct these harmonic currents, including transformers, switch gear, distribution bus, and cables, will have higher losses due to high-frequency heating effects. Another often-overlooked consequence of these line current harmonics is the error that they can cause in the trip level of circuit breakers.

### 7.3.3.2 Solutions to Power Factor and Harmonic Problems

Three possible approaches are available to solve rectifier power factor and harmonic problems.

---

**TABLE 7.1**

<table>
<thead>
<tr>
<th>Class</th>
<th>Line Notch Depth (%)</th>
<th>Line Notch Area (V-μs)</th>
<th>Voltage Total Harmonic Distortion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special applications</td>
<td>10</td>
<td>16,400</td>
<td>3</td>
</tr>
<tr>
<td>General system</td>
<td>20</td>
<td>22,800</td>
<td>5</td>
</tr>
<tr>
<td>Dedicated system</td>
<td>50</td>
<td>36,500</td>
<td>10</td>
</tr>
</tbody>
</table>

**TABLE 7.2**

Current Distortion Limits for General Distribution Systems (120 through 69,000 V)

<table>
<thead>
<tr>
<th>$I_{sc}/I_L$</th>
<th>$3 &lt; h &lt; 11$</th>
<th>$11 \leq h &lt; 17$</th>
<th>$17 \leq h &lt; 23$</th>
<th>$23 \leq h &lt; 35$</th>
<th>$35 \leq 50$</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>4.0</td>
<td>2.0</td>
<td>1.0</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>20–50</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>50–100</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>100–1000</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>

*a* Even harmonics are limited to 25% of the odd harmonic limits.

*b* Current distortions that result in a DC offset (e.g., half-wave converters) are not allowed.

*c* All power generation equipment is limited to these values of current distortion, regardless of actual $I_{sc}/I_L$, where $I_{sc}$ = maximum short-circuit current at The Point of Common Connection (PCC); $I_L$ = maximum demand load current (fundamental frequency component) at PCC.
7.3.3.2.1 Excess Installed Capacity
In some cases, the installed power electronic (rectifier) load can be restricted to a small amount of the total load served by the distribution branch. This is practical where a small IH power supply is used in a plant or area of a plant that is primarily operating non-power electronic loads. Providing excess capacity for the sole purpose of reducing harmonic distortion is seldom if ever economically feasible.

7.3.3.2.2 Filtering the Total Load
In some cases where there is a large amount of equipment with rectifier inputs, it is practical to filter the entire plant or branch circuit. This can be accomplished by passive or active filtering components or by phase staggering of various loads to obtain harmonic cancellation. This approach requires careful planning and is often not practical because significant loads such as large IH power supplies may be turned on and off randomly, which means an adaptive system is needed.

7.3.3.2.3 Active PWM Converter
The active PWM converter is actually a group of converter circuits that employ transistors (usually IGBTs) to reduce line current harmonic content, improve the input power factor, and control the output DC voltage as described in Section 7.3.1.4.

The cost and complexity of this solution to the power quality problem can be greater than that of the high-frequency inverter portion of the IH power supply. The robustness and reliability of this approach using transistors, under inverter fault conditions, are significantly less than conventional rectifiers using high-power SCRs or diodes. Development of active rectifier circuits is being aggressively pursued and will undoubtedly become a viable solution to both power factor correction and harmonic reduction.

7.3.4 Inverter Section
The inverter section of the power supply switches the DC or voltage to produce a single-phase AC output. The two most common configurations are the full bridge and half bridge, which are used in both voltage-fed and current-fed inverters.

7.3.4.1 Full-Bridge Inverter
The most common inverter configuration is the full bridge as shown in Figure 7.21. Often referred to as an H bridge, it has four legs, each containing a switch. The output is located in the center of the H so that when switches S1 and S2 are closed, current flows from the DC supply through the output circuit from left to right. When switches S1 and S2 are closed, current flows from the DC supply through the output circuit from left to right. When switches S1 and S2 are closed, current flows from the DC supply through the output circuit from left to right.

FIGURE 7.21
Basic full-bridge inverter.
opened and switches S3 and S4 are closed, the current flows in the opposite direction, from right to left. As this process is repeated, an alternating current is generated at a frequency determined by the rate at which the switches are opened and closed.

### 7.3.4.2 Half-Bridge Inverter

The half-bridge inverter, as its name implies, requires only two switches and two capacitors to provide a neutral connection for one side of the output circuit as shown in Figure 7.22. The other side of the output circuit is then switched between the positive DC supply by S1 and the negative supply by S2, thus generating an AC voltage across the output. This configuration is used in place of the full bridge where lower output voltage or output power is desired.

### 7.3.4.3 Voltage-Fed Inverters with Simple Series Load

Voltage-fed inverters are distinguished by the use of a filter capacitor at the input of the inverter and a series-connected output circuit as shown in the simplified power circuit schematic of Figure 7.23. The voltage-fed inverter is used in IH to generate frequencies from 90 Hz to as high as 1 MHz. Thyristors can be used to switch the current at frequencies below 10 kHz. Below 70 kHz, insulated gate bipolar transistors are commonly used. Above 70 kHz power, MOSFET transistors are usually chosen for their very fast switching speeds.

![FIGURE 7.22](image)

**FIGURE 7.22**
Basic half-bridge inverter.

![FIGURE 7.23](image)

**FIGURE 7.23**
Voltage-fed series connected output.
The voltage-fed inverter can be switched below resonance as illustrated by the bridge output voltage (Figure 7.24, trace 1) and the output current waveshape (trace 2). This must be the case when thyristor switches are used because diode conduction must follow thyristor conduction for sufficient time to allow the thyristor to turn off. This minimum turn-off time requirement limits the practical use of thyristors to frequencies below 10 kHz. The Inductoheat’s Statipower 6 is an example of this type of inverter.

Transistors do not require turn-off time and therefore can be operated at resonance as illustrated by the output current waveshape (Figure 7.24, trace 3). In this case, there is little or no diode conduction, and the transistor is switched while the current is at zero, thus minimizing switching losses and maximizing inverter power rating and efficiency. Operation at resonance means that the output power factor is unity and maximum power is being transferred from the DC source to the load. To regulate power in this case, the DC supply voltage must be controlled. The LSS family of power supplies (produced by Inductotherm India) is an example of this type; they are operated at resonance with power controlled by variable DC supplied by a switch mode regulator.

Transistors can also be switched above resonance as illustrated in Figure 7.24, trace 4. In this case, the conducting switches (S3 and S4) are turned off before the current reaching zero. This forces the current to flow in the diodes (D1 and D2) that are across the nonconducting switches (S1 and S2). These switches (S1 and S2) can then be turned on and will conduct as soon as the load current changes direction. This mode of operation minimizes transistor and diode switching losses while allowing the inverter to operate off resonance.
to regulate power. The Inductoheat’s Statipower 16 is an example of this type of inverter [643]. Control of inverter frequency relative to the natural resonant frequency of the load to regulate output power is discussed in Section 7.4.2.

The full-bridge voltage-fed inverter with pulse width modulated (PWM) switching of the bridge transistors can be supplied by a fixed DC and switch at the resonant frequency of the load. In this case, the power is controlled by varying the duty cycle of the inverter output. A separate square wave gate control signal is provided to each half of the inverter H Bridge while shifting the phase of one relative to the other. The greater the phase difference between the square waves, the lower the output power. The gate signals, bridge output, and the resulting output current for operation at reduced output power are illustrated in Figure 7.25.

The voltage-fed inverter supplies a rectangular wave voltage at the output of the bridge, and the impedance of the load determines the current drawn through the bridge to the series load circuit. In nearly all heat treatment applications, an output transformer is required to step up the current available from the inverter to the higher level required by the induction coil. The secondary circuit of this transformer is connected directly to the

---

**FIGURE 7.25**
Waveshapes of the PWM controlled voltage-fed series inverter at reduced power.

**FIGURE 7.26**
Bridge inverter features.
heating coil when the heating frequency is 30 kHz or less and the coil voltage is less than 250 V. In higher-frequency applications where the coil voltage is necessarily greater, the series resonant capacitor is usually placed in the secondary circuit of the transformer and in series with the heating coil.

The salient features of the voltage-fed inverter with a simple series resonant IH load are compared to those of the current-fed bridge inverter and summarized in Figure 7.26.

### 7.3.4.4 Voltage-Fed Inverter with Series Connection to a Parallel Load (LC-LC)

A popular variation of the voltage-fed inverter has an internal series-connected inductor and capacitor that couple power to a parallel resonant output or “tank” circuit. This topology commonly referred to as LC–LC is shown in Figure 7.27. The values of the internal series inductor and capacitor are selected to be resonant above the operating or firing frequency of the inverter with impedance at this firing frequency that will allow sufficient current to flow from the bridge to permit full-power operation. A very important feature of this style of inverter is that the internal series circuit isolates the bridge from the load. This protects the inverter from load faults caused by shorting or arcing and from badly tuned loads, making it one of the most robust thyristor-based induction power supplies available for heat treatment.

A second feature of this series-parallel configuration is realized when the internal series circuit is tuned to the third harmonic of the firing frequency. The power supply is then capable of developing full power into the parallel tank circuit tuned to either the fundamental firing frequency or the third harmonic. For example, the Inductoheat Statipower 5 family of induction heat treating power supplies is produced in three dual-frequency models, 1 and 3 kHz, 3.2 and 9.6 kHz, and 8.3 and 25 kHz with a power range of 75 to 1500 kW (Figure 7.28). Because load current is not used for commutation, this system can be operated with the output shorted for easy troubleshooting. Solid-state accuracy ensures output power regulation of less than ±1% with an input line variance of ±10%. Reliability is further enhanced by placement of 95% of all circuitry on one control board that is accessible without entering the high-voltage section of the power supply.

![Figure 7.27](https://example.com/figure7.27.png)

**FIGURE 7.27**
Voltage-fed inverter with series connection to parallel load.
The voltage-fed inverter with series connection to a parallel load commonly uses thyristors for power switching in the bridge and has an unregulated DC input supply. Regulation of output power is accomplished by varying the firing frequency relative to the parallel load resonant frequency. The waveshapes present in this style of inverter are shown in Figure 7.29. Trace 1 shows the voltage waveshape at the output of the bridge. Trace 2 shows the bridge current to the load and trace 3 is the load current and the current when the load is tuned to the fundamental or firing frequency. The corresponding waveshapes for operation with the load tuned to the third harmonic of the firing frequency are shown in Figure 7.29, trace 4.

7.3.4.5 Voltage-Fed Inverter with Series Inductor Connected to a Parallel Load (L–LC)

Another method for connecting a voltage source inverter to a parallel resonant load is commonly referred to as L–LC. Transistors (either IGBT or MOSFET) are the power switching components most commonly used in this type of inverter. Control of output power is accomplished by sweep frequency operation either below or above the load resonant frequency. In addition to sweep frequency control, PWM of the conduction time of the bridge switches may be used to control output power and limit the peak current. This PWM control allows for operation into a shorted load and also allows for testing of the power supply with its output short circuited. An example of L–LC inverter is the Inductoheat SP18 power supply [644].

7.3.4.6 Full-Bridge Current-Fed Inverters

Current-fed inverters are distinguished by the use of a variable-voltage DC source followed by a large inductor at the input of the inverter bridge and a parallel resonant load
A simplified power circuit schematic of the full or “H” bridge current-fed inverter is shown in Figure 7.30. Current-fed inverters are available in models that cover the entire 90-Hz to 1-MHz range of frequencies used for induction heat treatment. Thyristors are commonly used below 10 kHz, whereas transistors are chosen for the higher frequencies.

When the power switching is done with thyristors, the current-fed inverter must be operated above the resonant frequency of the parallel resonant load. As illustrated by the waveshapes of Figure 7.31, the voltage across the output of the bridge is a sine wave (trace 1) and the current (trace 2) is a square wave. It is interesting to note that this is just the reverse of the voltage-fed inverter, where the voltage is a square wave and the current is a sine wave. The DC bus voltage across the bridge after the large inductor $L_{dc}$ (trace 3) resembles a full-wave rectified sine wave. The bus voltage is forced negative from the time the bridge is switched until the load voltage reaches zero. This time must be sufficiently long to provide

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**FIGURE 7.29**
Waveshapes of voltage-fed inverter with series connection to parallel load.

**FIGURE 7.30**
Current-fed full-bridge inverter.
turn-off time to thyristors that are no longer conducting. The voltage across the thyristor switches is shown in traces 4 and 5 of Figure 7.31 with the negative portion of the waveform noted as the turnoff time. The TG, TC, and ICF families of power supplies (produced by Radyne Ltd, presently Induction Heating and Welding Ltd., UK) are of this design and have been in use since 1970.

The current-fed inverter uses transistors at frequencies above 10 kHz because they can be switched very fast and do not require turn-off time. In this case, the inverter can be operated at the resonant frequency of the parallel resonant tank circuit as shown in Figure 7.32.

![Current-fed inverter waveshapes above resonance.](image1)

![Current-fed full-bridge transistor inverter.](image2)
One diagonal of the bridge containing transistors T1 and T2 is turned on as transistors T3 and T4 of the other diagonal are turned off. This switching or commutation is done at a time when the voltage across the load, inverter bus, and transistors is zero.

The inverter waveshapes obtained in this mode of operation are shown in Figure 7.33. Switching at zero voltage minimizes the switching losses in the transistors and therefore allows for higher-frequency operation. When the inverter frequency is locked to the natural resonant frequency of the load, the output power must be regulated by controlling the input current to the inverter. This is accomplished by using one of the variable-voltage DC supplies described earlier. The Statitron® (produced by Inductotherm S.A., Belgium) uses MOSFET transistors in a current-fed configuration for heat treating at frequencies from 15 to 800 kHz with power levels up to 2 MW.

7.3.4.7 “E” Bridge Current-Fed Inverter

The E bridge current-fed inverter is shown schematically in Figure 7.34. The switches, typically IGBT or MOSFET transistors, are switched at resonant zero crossing of the load voltage to minimize switching losses. Using transistors of a given voltage rating, the E bridge topology permits use of two times the input voltage and double the output voltage compared to the conventional H or full-bridge topology. This makes the E bridge particularly attractive in applications supplying relatively high power to a high-voltage load coil.
7.3.4.8 Single-Switch Inverter

Another inverter configuration that has been used extensively for heat treating at 10 and 30 kHz uses only one thyristor and is referred to as a chopper or quarter bridge. Figure 7.35 shows a simplified circuit diagram. It is classified as a current-fed inverter because it has a large inductor in series with the DC supply to the inverter.

Unlike the conventional full-bridge current-fed inverter, the chopper has a series-connected output circuit. When the thyristor is switched on, current flows from both the DC source through the large inductor and also from the series load-tuning capacitor, discharging it through the load coil. The resulting load current pulse (Figure 7.36, trace 2) is nearly sinusoidal, with the first half-cycle of current passing through the thyristor and the second half-cycle through the diode. During this part of the period, current is rising in the input inductor. When current stops flowing in the diode, the energy stored in the input inductor causes DC to flow in the output circuit, recharging the series load-tuning capacitor.

The frequency of the output sine wave is determined by the series capacitor and the load coil inductance. It is this frequency that determines the penetration depth of the IH current. The firing rate of the inverter regulates the output power and therefore a simple fixed-voltage DC source may be used. The Inductoheat Unipower 9 and Uniscan induction scan hardening machine both make use of this simple inverter [628].

7.3.5 Advances in Power Supply Control

Since the beginning of the twenty-first century, changes in induction power supply design have been driven by the development and availability of powerful digital integrated circuits including microprocessors, microcontrollers, and field programmable gate arrays. The speed and reliability of these devices are such that they can be used to perform many...
functions previously accomplished by analog circuitry. Control functions most advanced by the availability of these devices include input interface, fault detection, annunciation, communication, and control performance field upgrade.

Power electronic circuit design and power electronic component development is now driven largely by automotive, appliance, wind, and solar energy conversion applications. The need for high voltage, high current, high switching speed, low inductance, and high reliability in these applications mirrors the requirements for these devices in IH power supplies. As a result, new and improved power and control components developed for other applications will find their way into IH inverters.

7.3.5.1 Circuit Boards

The use of surface mount electronic components on multilayer printed circuit boards is one of the most noticeable advances. While making control boards significantly smaller, this technology has improved noise immunity. The control circuitry is typically located in the inverter cabinet where fast switching of very high power can generate strong electromagnetic and electrostatic fields. Minimizing the size of circuitry and length of component interconnections as well as the inclusion of ground planes in multilayer PC boards dramatically reduces the chance for noise pickup in this electromagnetically noisy environment.

7.3.5.2 Fault Detection

The ability to detect a potentially damaging excessively high-current condition in transistor modules has led to the development of fast shutdown gate drive circuitry. Protecting a transistor from failure requires that the fault current be suppressed before too much heat is generated within the module. This protective circuitry is most effective in low- and medium-frequency inverters where the rate of rise of current ($d_i/dt$) allows sufficient time for shutdown before transistor failure.
7.3.5.3 Communication

Remote monitoring of equipment status is made possible by the inclusion of wired network or wireless connection to the power supply control. Computer data logging, statistical analysis, and part traceability are becoming commonplace. The ability to analyze inverter operating parameters such as command, feedback, and limit and trip signals to predict problems, diagnose faults, and prescribe maintenance activity is becoming a reality. This capability is attractive from the standpoint of improving performance and uptime. However, it should be recognized that the additional circuitry and system complexity may have a negative impact on overall system reliability.

The inclusion of a network connection to inverter control electronics also makes modification or upgrade of inverter control firmware possible from a remote manufacture’s facility.

7.3.6 Operational Considerations

Operational considerations that have an impact on the suitability of each type of power supply include initial cost, operating cost or overall efficiency, reliability, maintenance, flexibility, cooling water availability, and the power supply’s impact on utility power quality.

7.3.6.1 Initial Cost

Initial cost is important but should be a deciding factor only when all of the inverter types considered meet the other operational requirements. In general, the chopper or quarter-bridge power supply has the lowest purchase price. For power levels below 250 kW, the voltage-fed inverter with series resonant load is the next choice based on cost. The current-fed inverter has a low cost per kilowatt when high power at low frequency is required. The most expensive is usually the voltage-fed inverter with a series connection to a parallel load. It has more power components per kilowatt than any other type of inverter in its frequency range but is the most robust and flexible for IH applications.

7.3.6.2 Operating Cost

Operating cost, which is usually determined by the power conversion efficiency, is also a consideration. Modern semiconductor-based power supplies, however, all have reasonably high conversion efficiency compared to their motor generator and vacuum tube predecessors. Most have a conversion efficiency of 80% to 93% when running at rated output power. The conversion efficiency referred to here is that of the power supply from the input power connection to the output terminals and therefore does not include, in some cases, the output-matching transformer and load-tuning capacitors. Measurement and specification of power conversion efficiency can be accomplished in many ways with differing results. At one extreme, only the losses in the inverter portion are used in the calculation of efficiency. At the other extreme, all the losses from line to load are included by taking the ratio of the output power delivered to a calorimeter load to the input line power to the system. This method includes the losses in the induction coil, which can be relatively high, resulting in a much lower stated efficiency. It is therefore essential to know specifically what portions of the system are included in the specified efficiency to make direct comparisons of power supply efficiency.
7.3.6.3 Reliability and Maintainability

Reliability, maintainability, and a power supply’s tolerance to input and load perturbations are functions of power component design margin and control circuit design rather than the general type of power supply circuit used. Without carrying out a detailed analysis of a power supply, it is very difficult to assess its reliability. Barring this analysis, the best guide to equipment reliability is an assessment of the manufacturer’s reputation, how long they have been in the business of producing IH power supplies, and the amount of their equipment in field use. Maintainability is affected by many features of power supply design, including the level of self-diagnostics provided, accessibility of components for inspection and measurement, and ease of component and subassembly removal and replacement. When power components, subassemblies, and control boards are interchangeable without adjustment or modification, electrical maintenance personnel with only minimal training can quickly and effectively accomplish troubleshooting and repair. Self-diagnostic systems can be very helpful in locating failures in a power supply. However, the inclusion of diagnostic circuitry, which can also fail, has a negative impact on reliability and, therefore, a balance between the level of fault diagnostics and power supply reliability is necessary. A very reliable power supply design should require only very basic fault indicators, whereas more failure-prone designs should be equipped with more extensive diagnostics to speed the repair process even though an incremental decrease in reliability will result.

7.3.6.4 Flexibility

The ability of a power supply to operate under varying load conditions or in different applications is an important factor in some situations. If the heat treatment machine is general-purpose such as a scan hardening machine used in a job shop, the ability to match a wide range of coils at more than one frequency is attractive if not essential. In this case, a dual-frequency power supply with a versatile load-matching system, including both transformer tap switches and dual-frequency capacitor banks, is advantageous. The relatively new transistorized power supplies with external transformer tap switching are also attractive where their small size, light weight, and minimal cooling water requirements allow them to be portable and to be used by multiple machines [628]. A recently available IH power supply with ultimate flexibility provides a wide range of independent control of power and frequency. The Inductoheat IFP described later in Section 7.11 allows for instantaneous control of frequency from 5 to 60 kHz [645].

7.4 Load Matching

7.4.1 Prelude to the Discussion of Load Matching

A very important facet of IH that is often overlooked in the initial design stages is the ability to successfully deliver to the workpiece the maximum available power from a given power supply at the minimum cost. Circumstances do not always allow for optimal design of a complete IH system in which the power supply design is based on the application including the specific induction coil parameters. Quite often, the induction coil is designed to achieve the desired thermal conditions of the workpiece without regard for the power supply that will be used. When this is the case, a flexible interface is required to match the
output characteristics of the power supply to the input characteristics of the induction coil and workpiece combination [646]. If this match is not provided, the power supply may not be able to deliver its rated power because the coil requires more voltage or current than the supply can deliver.

The advantage of a full service supplier like Inductoheat is that a complete system can be designed from the workpiece to the matching components, transmission lines, and the power supply, ensuring full functionality to successfully process the workpiece in the most cost-efficient manner meeting all environmental requirements.

In many cases, a heat treat department will have a fixed number of power supply types of different power and frequency rating that must be used to complete the desired heating task. Also, because of the expense of designing and building a separate inductor (heating coil) for each workpiece, a coil may need to be selected from the fixed number and type of heating coils that are “on the shelf” to accomplish the task.

There are many factors involved, any of which can cause complications in arriving at the stated goal. To facilitate this matching process, variable-ratio transformers, capacitors, and sometimes inductors are connected between the output of the power supply and the induction coil. The adjustment of these components is commonly referred to as “load matching” or “load tuning.”

### 7.4.2 Understanding Load Matching for IH

#### 7.4.2.1 Basic Concept

A common example of matching a power source and load would be a simple lighting circuit application where a 6-V light bulb is available for use on a 120-V power line (Figure 7.37). Obviously, there is a need for some type of interface hardware to prevent the 120 V from destroying the light bulb. The likely solution would be to insert a transformer of suitable power rating between the light bulb and the power line, or a second solution, depending on the application, would be to connect 20 of the bulbs in series across the 120-V line. Either solution would suffice and both require knowledge of the operating characteristics of the source and of the load to provide a successful match.
7.4.2.1.1 The Load Circuit

To apply a similar rationale in the IH arena, we must begin with an understanding of the IH load circuit.

As illustrated in Figure 7.38, the generalized model for the induction coil and workpiece combination consists of two electrical components, resistance and inductance. The resistive component $R$, in ohms, causes heat to be generated. The inductive component ($L$), in henries, results from the magnetic field generated by the flow of alternating current through the heating coil. The opposition of current flow caused by inductance ($L$) is called inductive reactance ($X_L$) and is dependent on frequency ($X_L = 2\pi fL$).

$R_p$, the resistive component of the work coil copper; $R_s$, the reflective resistance of the secondary eddy current path in the workpiece to the primary circuit; $X_{lp}$, the primary reactance of the work coil; $X_{ls}$, the reactance of the secondary eddy current path reflected to the primary circuit; and finally, $X_{lg}$, the reflective reactance of the secondary air gap between the coil and the workpiece. The largest reactive component is $X_{lg}$ [1, 6, 648]. In the parallel circuit shown, the load power dissipated is given by the formula

$$P = I^2 \times (R_p + R_s).$$

The load current is the output voltage of the converter divided by the circuit impedance $E/Z$, where $Z = (R_p + R_s) + j(X_{lp} + X_{ls} + X_{lg})$.

This circuit would seem to be easy enough to analyze except for the fact that both resistance and the reactance of the circuit are nonlinear functions of several parameters such as coil–workpiece geometry, material properties, and frequency. Furthermore, the electrical resistivity and magnetic permeability of the metals are nonlinear functions of the temperature. At the same time, magnetic permeability is a nonlinear function of magnetic field intensity as well (Figures 3.3 through 3.12). As shown in Section 3.1, electrical resistivity and magnetic permeability vary during the heating cycle. In addition, for reasons of economics, modern metalworking processes require that workpieces of different sizes be heated in the same inductor. Combinations of the production mix and variation in material properties result in changing coil resistance and reactance, which affects the tuning and performance of the power supply. The combination of these factors indeed makes the light bulb a simple but illustrative case.

Generally speaking, a change in coil resistance and reactance results in a change of the phase angle between the coil voltage and the coil current of a given circuit. Such a change

![FIGURE 7.38](image-url)
can be characterized by the coil power factor, which refers to the cosine of the phase angle (cosine $\theta$).

Power factors of different types of inductors are affected differently by various parameters. At the same time, for different frequencies and different coil-to-workpiece air gaps, the power factor can be significantly different (i.e., cosine $\theta = 0.02$, up to cosine $\theta = 0.6$, which makes a Q-factor $((X_{lp} + X_{ls} + X_{lg})/(R_p + R_s))$ range from Q = 50 down to Q = 1.7.

Figures 4.18 and 4.23 illustrate the thermal dynamics of the typical induction heat-treating processes for a typical carbon steel workpiece. Temperature variations cause corresponding variations of coil electrical parameters. Chapter 3 provides a complete description of the theoretical background and modern computational methods for simulation of the IH process.

In conventional heat treatment, the applied frequency typically ranges from 200 Hz to 600 kHz. Since a relatively large current is required to successfully heat a workpiece, it is necessary to build power sources with sufficiently high output current capability or to use a simple resonant circuit to minimize the actual current or voltage requirement of the frequency converter.

### 7.4.2.2 A Simple Example

Given an induction coil that requires 100 kW, 40 V, and 10,000 A at 10 kHz and a power source that is rated at 100 kW, 440 V, and 350 A, are the two incompatible?

By using an isolation transformer, we might select a ratio of 440:40 or 11:1 to match the power source’s 440 V to the induction coil’s 40 V. This would leave us with a current requirement of 10000/11 or 909 A, which is too high for the given power source.

By the addition of a specific capacitance to the load circuit, it is possible to lower the current requirement and still accomplish the heating task. The addition of sufficient capacitance to tune the circuit to unity power factor (cosine $\theta = 1$) would result in a required current from the power source of 100 kW/440 V or 227 A, well within the limitations of our selected power source. This relaxes the requirements not only on the power source but also on interconnecting cables, contactors, and transformers operating in the area of the improved power factor.

### 7.4.2.3 Parallel and Series Connected Load Circuits

As shown in Section 7.3, resonant frequency converters use one of two types of load configurations, either parallel or series resonant circuits. Figure 7.39 shows the

![Figure 7.39](attachment:Figure7.39.png)

**FIGURE 7.39**
Resonance at parallel and series circuits.
characteristics of series and parallel resonant circuits. Looking first at the parallel circuit, it is easy to see that if the capacitance is equal to zero, then a given voltage applied to the circuit at a fixed frequency will result in a specific amount of power dependent on the circuit impedance. When sufficient capacitance is added to the circuit to tune the load circuit near resonance, the circuit impedance rises and the amount of current drawn from the power source falls off dramatically. The circuit voltage required to achieve a specific power level is the same as with the initial case of zero capacitance, but now most of the higher current required by the load is being supplied by the capacitors rather than the power source.

In a parallel-tuned load circuit, we have a $Q$ rise in current in the tank circuit compared with the input line from the power source (Figure 7.40). In a series connected load circuit, the impedance reaches a minimum at resonance. Therefore, to obtain the necessary coil current, the driving voltage will be a factor of $Q$ lower than the coil voltage. Hence, relative to the input line from the power source, we have a $Q$ rise in current in the parallel circuit and a $Q$ rise in voltage with the series-connected circuit (Figures 7.39 and 7.40). It is therefore imperative to have an understanding of what type of circuit connection exists in order to understand the effect that changes in value of the tuning components will have on the power source and workstation components.

### 7.4.2.4 Load-Matching Procedures

There are typically nine steps to be taken in matching the power supply to the IH load.

1. Determine the output ratings of the power supply and maximum rating of matching components.
2. Estimate load coil input needed to obtain the desired heating result.
3. Estimate the $Q$ of the work coil.
4. Determine the voltage on matching capacitors and transformer.
5. Calculate the value of the matching capacitor.
6. Calculate the ratio of the matching transformers.
7. Make a trial run and record indicated power, voltage, and frequency.
8. Recalculate matching circuit values based on the trial run if necessary.
9. Make a trial run and repeat Step 8 if necessary.
Knowledge of the relationship between the various load circuit parameters is helpful to successfully accomplish effective load matching. The following equations define these important relationships:

\[ X_L = 2\pi fL \]
\[ Q = X_L / R \]
\[ X_C = 1/(2\pi fC) \]

\[ \text{kVAR} = 2\pi fCV^2 /1000 \]
\[ \text{kVA} = kW \times Q \]
\[ f_R = 1/(2\pi \sqrt{LC}) \]
\[ I_C = V \times 2\pi fC \]

At resonance:

\[ X_L = X_C \]

\[ \text{kVAR} = \text{kVA} \text{ (approximately)} \]

\[ C = 10^3 \times kW \times Q / (2\pi fV^2) \]

Transformer relationships:

\[ N_P / N_S = V_P / V_S = I_S / I_P \]
\[ \text{kVA}_P = \text{kVA}_S \]
\[
X_{LP} = (N_p/N_s)^2 \cdot X_{LS}
\]

\[
X_{CP} = (N_p/N_s)^2 \cdot X_{CS}
\]

\[
Z_p = (N_p/N_s)^2 \cdot Z_s
\]

where

- \( f \) = frequency
- \( R \) = resistance in ohms
- \( L \) = inductance in henries
- \( X_L \) = inductive reactance in ohms
- \( Q \) = coil quality factor
- \( C \) = capacitance in farads
- \( I_C \) = capacitor current in amperes
- \( X_C \) = capacitive reactance in ohms
- \( kVAR \) = product of voltage and current in a capacitor/1000
- \( kVA \) = product of voltage and current in the load/1000
- \( kW \) = power in watts/1000
- \( f_R \) = resonant frequency
- \( N_p \) = transformer primary turns
- \( N_s \) = transformer secondary turns
- \( V_p \) = primary voltage
- \( V_s \) = secondary voltage
- \( I_p \) = primary current
- \( I_s \) = secondary current
- \( X_{LP} \) = inductive reactance in ohms measured at the primary
- \( X_{LS} \) = inductive reactance in ohms measured at the secondary
- \( X_{CP} \) = capacitive reactance in ohms measured at the primary
- \( X_{CS} \) = capacitive reactance in ohms measured at the secondary
- \( Z_p \) = impedance in ohms measured at the primary
- \( Z_s \) = impedance in ohms measured at the secondary

### 7.4.2.4.1 Matching the Parallel Resonant Load

The load-matching procedures described here all involve operating near resonance at a frequency that is required to obtain the desired heating effect. Figure 7.41 shows the effect of inverter operation frequency relative to load resonance frequency on inverter output power.

- Step 1—Determine the output rating of the power supply and maximum rating of matching components.

For this example, the 10-kHz power supply has a power rating of 100 kW, a maximum output voltage rating of 800 V, and a maximum output current of 250 A. The capacitor and transformer have a maximum voltage rating of 800 V.
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- Step 2—Estimate the power, frequency, coil voltage, and coil Q.
  
  Based on process modeling or on previous experience with a similar part/coil combination, the following estimates will be used. The induction coil requires a power of 80 kW, a coil voltage of 50 V, and a heating frequency of 9.5 kHz.

- Step 3—Estimate the Q of the heating coil.
  
  For the purpose of this example, a coil Q of 4 will be used.

- Step 4—Calculate the capacitor voltage.
  
  If the maximum capacitor voltage is 800 V, the voltage on the capacitor at 80 kW is found by

  \[ V_C = 800 \frac{80}{100} = 715 \text{ V} \]

- Step 5—Calculate the capacitance of the matching capacitor.
  
  The capacitor value in microfarads is found by

  \[ C = \frac{10^9 \times \text{kW} \times Q}{2\pi V^2} = \frac{10^9 \times 80 \times 4}{2\pi \times 9500 \times (715)^2} = 10.5 \mu\text{F} \]

- Step 6—Calculate the transformer ratio.
  
  The transformer ratio is the ratio of output or capacitor voltage to coil voltage:

  \[ T_R = \frac{715}{50} = 14.3; \]

  therefore, a ratio of 14:1 will be used.

- Step 7—Run a trial heating cycle with the above matching component values.
  
  During this heating cycle, the actual power, voltage, and operating frequency are recorded so that estimates can be refined and the load match can be improved. In this example, the following data taken during the trial run will be used.

  Power = 75 kW, Voltage = 800 V in limit, Frequency = 9.0 kHz

---

**FIGURE 7.41**

Power curves for series and parallel output circuits.
Using these data, the actual \( Q \) of the heating coil can be calculated by rearranging the formula for capacitance used in Step 5 above.

\[
Q = \frac{2\pi CV^2}{10^9\text{kW}} = \frac{2\pi \times 9000 \times 10.5\mu\text{F} \times (800)^2}{10^9 \times 75\text{kW}} = 5.1
\]

- Step 8—Recalculate matching circuit values based on the trial run if necessary.

Since the trial run resulted in an output volt limit at less than the 80 kW desired, the following calculations are made to obtain circuit values that will provide a better match to the load.

The coil voltage at 75 kW is then 800 V/14 or 57 V.

To increase the power to 80 kW at 715 V, the coil voltage is found by

\[
\text{Coil voltage} = 57\sqrt{\frac{80}{75}} = 59\text{ V}.
\]

The new transformer ratio is found by

\[
T_k = \frac{715}{59} = 12.12;
\]

therefore, a ratio of 12:1 will be used.

A change in transformer ratio will change the resonant frequency by the inverse of the transformer ratio change.

\[
F = 9.0\text{ kHz} \left( \frac{14}{12} \right) = 10.5\text{ kHz}
\]

Since the resonant frequency varies inversely as the square of the capacitance, the value of the capacitor needs to be increased to lower the frequency to the desired 9.5 kHz.

\[
C = 10.5\mu\text{F} \left( \frac{10.5\text{ kHz}}{9.5\text{ kHz}} \right)^2 = 12.8\mu\text{F}
\]

- Step 9—Another trial run should be done to verify that the new transformer ratio and capacitor value provide the desired load match. If an acceptable match was not obtained, Step 8 should be repeated.

7.4.2.4.2 Matching the Series Resonant Load

As mentioned in Section 7.4.2.3, the impedance of the series connected load circuit reaches a minimum at resonance and the voltage supplied to the circuit is approximately a factor
of $Q$ lower than the voltage across the series capacitor. The two most common series load circuits are shown in Figures 7.42 and 7.43. Figure 7.42 shows a single transformer arrangement used for high-frequency/high-voltage loads.

Figure 7.43 for low-voltage loads requires two transformers and will be used in the following load-matching example. The load-matching procedures described here all involve operating near resonance at a frequency that is required to obtain the desired heating effect. For direct comparison purposes, the power supply and load parameters used in the parallel load tuning example above will be used here in the series circuit tuning procedure.

- Step 1—Determine the output rating of the power supply.

As in the previous example, the 10-kHz power supply has a power rating of 100 kW and a maximum output current of 250 A. The output voltage is 675 V as opposed to 800 V in the previous example. The capacitor and transformer have a maximum voltage rating of 800 V.

- Step 2—Estimate the power, frequency, coil voltage, and coil $Q$.

Based on process modeling or on previous experience with a similar part/coil combination, the following estimates will be used. The induction coil requires a power of 80 kW, a coil voltage of 50 V, and a heating frequency of 9.5 kHz.

- Step 3—Estimate the $Q$ of the heating coil.

For the purpose of this example, a coil $Q$ of 4 will again be used.

- Step 4—Calculate the capacitor operating voltage.

If the maximum capacitor voltage is 800 V, the voltage that should be on the capacitor at 80 kW is found by

$$V_C = 800\sqrt{\frac{80}{100}} = 715\text{ V}.$$

![FIGURE 7.42](series_resonant_high_voltage_load_circuit.png)

Series resonant high-voltage load circuit.

![FIGURE 7.43](series_resonant_low_voltage_load_circuit.png)

Series resonant low-voltage load circuit.
• Step 5—Calculate the capacitance of the matching capacitor.

The capacitor value in microfarads is found by

\[
C = \frac{10^8 \cdot \text{kW} \cdot Q}{2\pi V^2} = \frac{10^8 \cdot 80 \cdot 4}{2\pi \cdot 9500 \cdot (715)^2} = 10.5 \mu\text{F}.
\]

• Step 6—Calculate the transformer ratio.

At resonance, the voltage on the primary of the load-matching transformer will equal the series capacitor voltage. Therefore, the load-matching transformer ratio is the same as the ratio of capacitor voltage to coil voltage:

\[
T_R = \frac{715}{50} = 14.3;
\]

therefore, a ratio of 14:1 will be used.

As discussed in Section 7.4.2.3, to obtain the necessary coil current in the series connected load, the driving voltage will be a factor of \( Q \) lower than the coil voltage. The coil voltage in this case is the voltage on the primary of the load-matching transformer. Therefore, the voltage at the secondary of the output transformer is

\[
V_s = \frac{715 \text{ V}}{Q} = \frac{715 \text{ V}}{4} = 178 \text{ V}.
\]

Then, the ratio of the output transformer is the ratio of power supply output voltage on the primary to the secondary voltage \( V_s \):

\[
T_O = \frac{675 \text{ V}}{178 \text{ V}} = 3.8;
\]

therefore, a ratio of 4:1 will be used.

• Step 7—Run a trial heating cycle with the above matching component values.

During this heating cycle, the actual power, voltage, and operating frequency are recorded so that estimates can be refined and the load match can be improved. In this example, the following data taken during the trial run will be used.

\[
\begin{align*}
\text{Power} &= 75 \text{ kW}, \\
\text{Voltage} &= 800 \text{ V in limit}, \\
\text{Frequency} &= 9.0 \text{ kHz}
\end{align*}
\]

Using these data, the actual \( Q \) of the heating coil can be calculated by rearranging the formula for capacitance used in Step 5 above.

\[
Q \approx \frac{2\pi f CV^2}{10^9 \text{kW}} = \frac{2\pi \cdot 9000 \cdot 10.5 \mu\text{F} (800)^2}{10^9 \cdot 75 \text{kW}} = 5.1
\]
• Step 8—Recalculate matching circuit values based on the trial run if necessary.

Since the trial run resulted in an output volt limit at less than the 80 kW desired, the following calculations are made to obtain circuit values that will provide a better match to the load.

The coil voltage at 75 kW is then 800 V/14 or 57 V.
To increase the power to 80 kW at 715 V, the coil voltage is found by

\[
\text{Coil voltage} = 57 \sqrt{\frac{80}{75}} = 59 \text{ V.}
\]

The new transformer ratio is found by

\[
T_r = \frac{715}{59} = 12.12;
\]

therefore, a ratio of 12:1 will be used.

A change in transformer ratio will alter the resonant frequency by the inverse of the transformer ratio change.

\[
F = 9.0 \text{ kHz} \left( \frac{14}{12} \right) = 10.5 \text{ kHz}
\]

Since the resonant frequency varies inversely as the square of the capacitance, the value of the capacitor needs to be increased to lower the frequency to the desired 9.5 kHz.

\[
C = 10.5 \mu F \left( \frac{10.5 \text{ kHz}}{9.5 \text{ kHz}} \right)^2 = 12.8 \mu F
\]

Recalculating the voltage at the secondary of the output transformer:

\[
V_s = \frac{715 \text{ V}}{Q} = \frac{715 \text{ V}}{5.1} = 140 \text{ V.}
\]

Then, the ratio of the output transformer is

\[
T_o = \frac{675 \text{ V}}{140 \text{ V}} = 4.8;
\]

therefore, a ratio of 5:1 will be used.

• Step 9—Another trial run should be done to verify that the new transformer ratios and capacitor value provide the desired load match. If an acceptable match was not obtained, Step 8 should be repeated.
7.4.2.4.3 Trial-and-Error Method of Load Matching

Another common approach to load matching does not require mathematical calculations. This trial-and-error method usually takes more time and wastes more workpieces to obtain an acceptable match to the heating load. Using the trial-and-error approach involves setting up the load-matching transformer ratios and capacitor values based on previous experience or just an educated guess, followed by conducting a trial heat run to obtain meter readings, adjusting one matching component value, and making another heat run to determine the next change required. The chart in Figure 7.44 indicates the direction of change that should be made in a matching component, increase or decrease, based on the power supply meter readings.

![Figure 7.44](image.png)

**FIGURE 7.44**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Change</th>
<th>Adjust</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Capacitor</td>
</tr>
<tr>
<td>Voltage</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>Increase</td>
<td>Decrease</td>
</tr>
<tr>
<td>Current</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td></td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>Frequency</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>Increase</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

7.4.2.5 Load-Matching Component Connections

An often neglected factor in load-matching has to do with the transmission lines from the power source to the heat station (load-matching components) and those from the load-matching capacitors or output transformer to the heating coil. Large inductances in these areas can cause considerable problems because a significant portion of the voltage generated by the power supply may be dropped across the high-inductance elements of
the circuit and not across the load itself. This can result in a considerable reduction in
allowable output power and possibly in the inability to complete the desired heating
task. This inductance is particularly critical in the higher kilovolt-ampere portion of the
circuit (between the matching capacitors and the coil), especially at higher frequencies
and higher currents. A good practice is to minimize the transmission line inductance
within the required cost and size constraints to stay below a 10% voltage drop and 5%
kilowatt loss.

Techniques for reducing transmission line inductance include the use of coaxial cable,
properly bundled cables, and close spaced parallel bus.

7.4.2.5.1 Coaxial Cable
A coaxial cable (Figure 7.46) has a center conductor surrounded by an outer conductor with
insulation in between them. This configuration provides extremely low inductance but is
expensive to use in high-current applications.

7.4.2.5.2 Bundled Cables
Care in bundling output cables can greatly reduce inductance. Figure 7.47 shows the proper
way to bundle groups of 2, 4, 6, or 12 cables.

7.4.2.5.3 Parallel Bus Bar
A parallel bus bar, shown in Figure 3.17, is often used to conduct high current to the heat-
ing coil. The inductance of the bus bar connection is minimized by using a thin insulator
between the bus bars, allowing them to be closely coupled while providing the neces-
sary insulation to support the voltage between the bars. The resistance of the bus bar is
inversely proportional to its width so a wider bus will have lower losses. Another advan-
tage of a parallel bus is that it is easy to water cool.
7.4.3 Summary

In summary, although the IH process is a complicated dynamic process, the load-matching process need not be. If the information presented above is applied with careful collection of data during the process, the correct setup can be accomplished in a relatively short time by

- Starting with an estimated required kilowatt, voltage, and coil $Q$
- Establishing the correct resonant frequency
- Calculating or estimating transformer ratios and capacitor values
- Running a test cycle and gathering data at a specified time in the cycle
- Extrapolating from the existing readings to the desired readings
- Resetting the component values
- Running another cycle to evaluate the results

7.5 Medium- and High-Frequency Transformers for Heat Treating and Mass Heating

The transformer is an important part of the IH machine. Different types of transformers are used in inverters and heat stations [650–652]. The total efficiency of the power supply is primarily affected by the transformer’s efficiency. Years ago, when motor generators were widely used, the design of isolation transformers was a straightforward process. Basic information, such as frequency, kilowatts, kilovolt-amperes, and input/output voltages, was all that was required. Today, with many different types of solid-state inverters and heat stations, the task of designing efficient transformers becomes more complex. The successful design of contemporary transformers should involve operating parameters that include the current and voltage waveforms, which can be square, sinusoidal, or saw-tooth, and may have DC current offset.

The transformer’s main purpose is to change one voltage to another, making it possible to operate a great variety of loads at suitable voltages. In a transformer, the turns of the primary and secondary coils are coupled closely together so that their respective turns ratios determine very closely the output voltages and volt-ampere characteristics. The coils are usually wound on a core of laminated or ferrite magnetic material. In radio frequency transformers used with vacuum tube oscillators, there is no magnetic core. In this case, the transformer is called an aircore transformer.

Transformer manufacturers including the Jackson Transformer Company provide the IH industry with a wide range of transformers and other magnetic products from line frequency to 800 kHz, from a few volt-amperes to several thousand kilovolt-amperes, and with water- and air-cooled designs [650–652]. Products include isolation, auto, current, potential, and radio frequency transformers, along with AC/DC reactors and integrated magnetic devices. As a general rule, most of the magnetic devices are water cooled. This is because of size limitations, cost factors, power requirements, and the frequency ranges they cover.
7.5.1 AC/DC Reactors

AC reactor designs may be used from a few hertz to several hundred kilohertz, are water cooled or dry, and of open construction or are encapsulated. Reactors using an iron core must be gapped to accommodate direct current. The legs of the inductors wound on magnetic cores have distributed gaps to minimize flux leakage and to reduce audible noise. The legs are normally encapsulated to minimize vibrations. They are available from a few microhenries to several millihenries and from a few amperes to several thousand amperes.

7.5.2 Instrumentation Transformers

Measuring the operating current and voltage of the inverter is necessary for monitoring and control. This is often accomplished by instrumentation transformers that reduce these high currents and voltages to low-level signals that are appropriate for circuitry monitoring and controlling the current, voltage, and power of the power supply. Current transformers (CT) and potential transformers (PT) have a very low VA rating (50 VA or less) since they only drive control circuitry. Electronic circuits including differential voltage amplifiers, Hall effect, and Rogowski current transducers have begun to replace these transformers.

7.5.3 Heat Station Transformers

Jackson heat station transformers such as the 52V1, 51V1, and 531V1 have become the standard used in the heating, hardening, and annealing industry. 52V1 transformers (Figure 7.48a) are normally used where the voltage needs to be stepped down from 5:1 to 22:1 or from 5:2 to 22:2 or other ratio combinations depending on customer requirements. The input voltages are from 220 to 1200 V, and frequencies are from 500 Hz to 10 kHz. The kVA rating can range from 50 to more than 10,000 kVA.

The construction of the windings as shown in Figure 7.48b can be either open or epoxy-encapsulated. The output connections (secondary terminals) are generally referred to as fish-tails. The input side of the transformer, the primary winding, is tapped to cover the required turns ratio. The windings use rectangular copper tubing of the thin wall, which is acceptable because penetration depth of the current into copper at 10 kHz is only 0.7 mm.

FIGURE 7.48
Heat station transformer (a) and epoxy-encapsulated windings of transformers (b). (Courtesy of Jackson Transformer Company.)
A typical profile of the tubing used would be 6.35 mm × 25.4 mm × 1.2 mm (0.25 in. × 1 in. × 0.048 in.) wall. The primary and secondary windings are of an interleaved design to take advantage of the shape of the tubing and to reduce the resistance and impedance of the transformer. One of the unique features of this design is that the losses in the primary and secondary windings are equal. For a typical 22:1 ratio transformer, there are 22 primary turns in series and there are 22 secondary turns connected in parallel in a one-turn construction.

The construction of the core uses thin permeable steel 0.15 or 0.18 mm thick (0.006 or 0.007 in.) of EE- or EI-type laminations as shown in Figure 7.49. The core is water-cooled by means of copper cooling plates sandwiched between the steel laminations. It has been concluded after many tests that the flux generated by the ampere-turns in the magnetic circuit flows along the inside legs of the laminations just as current in a circuit takes the least resistive path. Therefore, the width of the outside legs of a shell-type transformer operated at medium frequencies can be less than one-half the tongue (center leg), as is required for low-frequency designs. The core losses of the outside legs will be higher than the losses of the center leg, which is acceptable, because the outside legs are cooled more effectively than the center. The core loss of the transformer varies as the square of the input voltage, inversely as the square of the input turns, and approximately as the fourth root of the frequency.

**7.5.4 Ferrite-Core Transformers**

Ferrite-core transformers, as shown in Figure 7.50, are similar to laminated core heat station transformers in that they can have an interleaved winding construction. The main difference is that in place of the steel laminations used in the core, ferrite material is used. The electrical resistivity of ferrites is much higher than laminations, resulting in lower eddy current losses in the ferrite cores. Having a homogeneous ceramic structure and inherent low core loss, the ferrites are very attractive for transformer applications at frequencies above 10 kHz. Even though the ferrite core loss is low, they may still need to be water-cooled in some cases, because of the high frequencies at which they are used. In applications when the output power from the power supply is fairly low and the frequency is under 10 kHz, ferrites are more advantageous than steel because of the lower loss of the ferrite. In many cases, this difference in core loss eliminates the need for water cooling of the ferrite cores and it also manifests itself into a respected difference in electrical efficiency.
Some designs of the ferrite core isolation transformer utilize Litz wire for the primary winding on a water-cooled copper secondary. This construction has two noteworthy advantages. The primary has very low losses at high-frequency because the Litz wire minimizes skin and proximity effects. Second, the Litz wire primary is indirectly cooled by the secondary but is not in direct contact with the cooling water. This means that low conductivity cooling water is not required and the primary will not be affected by electrolysis.

7.5.5 Toroidal Transformers

Typically, toroidal transformers are totally encapsulated, as shown in Figure 7.51, and are used in hardening, tempering, forging, and annealing. Normally, the output voltages are higher than in the heat station transformers. In many instances, the output voltage is equal to or much higher than the applied voltage. Input voltages can be from 100 to 2000 V or higher. The output voltages can range from 50 V to several thousand volts. Taps are provided within the voltage range. The frequencies can be from 200 Hz to 10 kHz. The
kilovolt-ampere can range from 50 to 3000 kVA or higher. They are more efficient than laminated transformers, have virtually no air gaps, and will not tolerate DC offset current. A disadvantage of being encapsulated is that they are not easily repaired and therefore are usually replaced when they fail.

Toroidal autotransformers are typically smaller in size and have lower exciting current, better regulation, and higher efficiency than an isolation transformer. This is because in an isolation transformer, all the kilovolt-amperes are transferred to the secondary, whereas in an autotransformer, only a portion of the total kilovolt-ampere is transformed; the rest flows directly from the primary to the secondary without transformation. The windings in an autotransformer are wound around the same core and are used to step up or step down the input voltage.

The core of toroidal transformers consists of a thin steel strip wound in a cylindrical or toroidal form. Water-cooled copper heat sinks are often used on the flat surface of the cores to carry away the heat generated by the core. Without water cooling, the physical size of the core would increase drastically. The windings are hand-wound over the core, using round copper tubing, its size being determined by the design current.

### 7.5.6 Integrated Magnetic Transformers

The Jackson Transformer Company has developed and patented a method of combining a transformer and inductor in a single package whereby the inductor and the primary of the transformer have a common core [653]. This product is referred to as a transinductor and can be designed to provide a fixed inductance in the primary or secondary or both. Variable ratios can be provided on the transformer portion. By combining the two components, the size of the product is reduced, the overall efficiency is increased, and the leakage flux of the magnetic device is minimized.

### 7.5.7 Rectangular (C-Core) Transformers

The construction of a rectangular transformer uses a C core and interleaved windings. Normally, the unit is epoxy-encapsulated, as shown in Figure 7.52. The design of the rectangular core transformer is usually for low to medium frequency with input voltages from a few hundred to a few thousand volts, output voltages from a few hundred to a few thousand volts, and input power up to several thousand kilovolt-amperes. Specific requirements for this type of transformer are low leakage, low inductance, and high efficiency.

*FIGURE 7.52*

Rectangular (C-core) transformer. (Courtesy of Jackson Transformer Company.)
7.5.8 Narrow-Profile Transformers

Narrow-profile transformers are designed to deliver high power at medium frequencies within narrow physical constraints. A typical example as shown in Figure 7.53 is used for the rotational IH of bearing surfaces on an engine crank shaft. A series of narrow-profile transformers can be placed side by side for simultaneous IH of a number of different bearing surfaces on an engine crank shaft. The construction of this style of transformer uses the interleaved winding design and ferrite cores and is epoxy-encapsulated. This allows the transformer to achieve its narrow-profile, high-efficiency, low-leakage inductance and be completely protected from its harsh environment and physical abuse.

7.5.9 Air-Core Radio Frequency Transformers

The air-core radio frequency (RF) transformer shown in Figure 7.54 is normally referred to as a current transformer and is designed without any core material. The critical element in the design is to obtain the highest current transfer ratio from primary to secondary. Generally, the primary winding is encapsulated in silicon rubber, which is a moisture-resistant material. This is required to prevent corona and voltage breakdown because of the high dielectric stress between the primary and secondary. It is also required to protect

![Figure 7.53](image1)

Narrow-profile transformer. (Courtesy of Jackson Transformer Company.)

![Figure 7.54](image2)

Air-core radio frequency transformer. (Courtesy to Jackson Transformer Company.)
the windings from the environment. Great care must be taken in the selection of material and construction. Manufacturing of this transformer is usually performed in a clean room environment.

7.5.10 Maintenance, Sizing, and Specification of Transformers

As a general rule, when transformers are water cooled, most failures occur because of a breakdown of the insulation between the windings. Normally, this is attributed to lack of water, poor-quality water, too high a water inlet temperature, or operation of the transformer outside its designed rating. Sometimes, insulation breaks down because of the harsh environment to which the transformer is subjected. Another failure that commonly occurs is the melting of the output connection. This can be caused by improper tightening or poor maintenance of the inductor (e.g., dirt or severe oxidation on the mating surfaces). Occasionally, the core may fail because of lack of water, poor-quality water, too many input volts per turn (voltage per turn exceeds core loss temperature limitation), and use at the inappropriate frequency. A well-designed water system will pay for itself with reductions in component failures and downtime. Proper maintenance of the inductor-to-transformer connections will also help greatly.

To properly size or specify a transformer, the following information is generally required:

- Input voltage to the transformer, power source wattage, the frequency range of the power source, and the frequency at which the transformer will operate
- The turns ratio or the output voltage required at full load (or no load)
- The input kilovolt-ampere at the minimum and maximum turns ratios
- The expected efficiency (based on the kilowatt rating of the power source) or kilowatt loss of the transformer
- Maximum duty cycle and maximum heat on time

It is also helpful to know any unique characteristics of the power source, type of waveform, and if any DC will be present. The more information the designer has available, the more assurance the customer has of getting the proper, most efficient transformer.

7.6 Special Considerations for Power Supplies

As described in previous chapters there is a wide variety of induction heat treatment processes. These include selective surface hardening, annealing, tempering, stress relieving, and through hardening. Before the use of IH, these processes were accomplished by batch heating in a furnace. IH allows for inline heat treatment using machines with these special power supply considerations:

- Less than 50% duty cycle
- Rapid cycling of heat on and off
- Precise control of power and time, and
- Minimum utilization of floor space
7.6.1 Duty Cycle

The induction heat-treating cycle in most cases consists of time to load the individual part or workpiece and move to the heating position, heat, quench, and unload the part. The heating portion of this cycle is usually less than 50% of the total cycle. This means that some portions of the power supply can be designed to safely take advantage of lower average losses that result from less than continuous duty operation. The most significant factor affected by duty cycle is the sizing of the cooling system required for the power supply. This is discussed in more detail in Section 7.12. There are some components of the power supply that heat and cool relatively slowly, including the load-matching transformer, internal interconnect cabling or bus bars and the DC choke that can also be sized to take advantage of limited duty cycle operation. Some components such as power semiconductors, fuses, and circuit breakers cannot be derated because of a low duty cycle.

7.6.2 Rapid Cycling of Heat On and Off

The semiconductor modules of transistors and diodes used in many modern IH power supplies are subject to power cycling failure. During each cycle, the semiconductor chip heats and cools, causing stress owing to the thermal cycling: the higher the power dissipation in the semiconductor, the greater the change in temperature and the higher the thermal stress. Semiconductor manufacturers provide curves, as shown in Figure 7.55, which relate temperature excursion to the number of cycles that can be expected before failure. This means that the rating of the power semiconductor modules in terms of power supply output power must be less for a cycling operation than for continuous duty operation.

7.6.3 Precise Control of Power and Time

The heating time in many applications is very short to avoid conduction of heat outside the desired hardness pattern area. In contour hardening, for example, heat times of less than 1 s are common. This means that the control of heat time must have high resolution (typically 0.001 s) and be repeatable and accurate. It also requires that the time required by the power supply to ramp up to set power at heat on and down at heat off must be short and repeatable.

![Figure 7.55](image-url)

Power cycling of IGBT modules (accelerated reliability testing of IGBT modules).
7.6.4 Minimum Utilization of Floor Space

During the past few years, manufacturers of induction equipment made significant progress in developing highly efficient, compact heat-treating systems [626]. The space savings were achieved by technical innovations in the area of electrical power devices, electronic systems, and equipment design. Many new power supply designs were introduced during this same period. Most of these designs use MOSFET or IGBT fast switching power transistors. Other factors, which have also had a significant influence on the ability to conserve existing shop floor space, are innovations in design concept, new mechanical components, and the continued growth of microprocessor and microcontroller technology resulting in sophisticated control/monitoring systems.

Equipment design has become holistic. The equipment now consists of a minimum of components and is more reliable, compact, and easier to operate and maintain. By designing with the whole system in mind, the floor space can be best utilized. For example, if the whole machine is more compact, the distance over which the water is pumped is shorter and the pump sizes can be smaller. All of these items work to the advantage of the purchaser by keeping cost and floor space to a minimum.

7.7 Special Considerations for Induction Brazing, Soldering, and Bonding

The application of IH for joining operations including brazing, soldering, and bonding has been discussed in Section 5.1. The power supplies used for these applications have these special requirements and operational considerations:

- Relatively low power.
- Medium to high frequency.
- Small size, often portable.
- Load-matching flexibility.
- Load Q is typically high.
- Operator manipulation of the heating coil is often required.

Joining operations require the heating of adjacent surfaces so that a filler material can be melted on these surfaces and then allowed to solidify to produce a solid joint. It is important therefore to be able to direct the heat uniformly into the areas to be joined without unnecessarily heating adjacent areas. This is done primarily by heating coil design but is also influenced by the characteristics of the power supply. The area that is joined by induction brazing or soldering is usually kept small because it is more practical to precisely control the heating of small areas than larger areas. This means that the power required is relatively low, usually in the range from 1 to 50 kW.

Heating of only the surface of the workpiece implies, as discussed in previous chapters, that the frequency be relatively high. For example, for a penetration depth of 0.5 mm, the heating frequency would be approximately 10 kHz for carbon steel when using low power density at room temperature. To obtain the same penetration depth, 20 kHz is required to heat copper and 70 kHz is required for brass. An even more compelling reason to use high
frequency for brazing, soldering, and bonding is that the higher the frequency, the smaller the current needed to do the same heating. This means that the heating coil and the conductors carrying current to the coil become smaller at higher frequencies. At the same time, the use of a higher frequency means electromagnetic components such as transformers used in the power supply and for load matching at the heating coil can be made more compact and lighter because smaller magnetic cores can be used. Thus, the use of high frequency allows for the use of smaller, lighter, and more portable equipment while providing the low power consumed heating.

In many applications of brazing and soldering, the process must be accomplished in a confined and often difficult to reach location. A small portable power supply such as the 5- to 15-kW Radyne Corp. VersaPower Xtreme shown in Figure 7.56 may be hand carried and placed where the heating is to be performed.

Power supplies designed for brazing and soldering are capable of matching a wide variety of heating coils. Those coils are often fabricated by forming copper tubing around the part to be heated and then bending it to obtain the desired heating pattern or CNC machined applying the results of computer modeling. As an example, Figures 5.4 through 5.6 show the different sizes and shapes that are commonly used for this application.

Many of these coils have loose coupling to the workpiece and often heat nonmagnetic material, which results in a high \( Q \) load. This means that the power supply must be capable of providing a high output kilovolt-ampere–to–kilowatt ratio.

7.8 Special Considerations for IH Power Supplies in Mass Heating Applications

Before 1970, the induction power supply used for heating large billets, bars, or slabs was single-phase line frequency. For somewhat smaller workpieces, frequency multipliers employing
saturable reactors were used to provide 180 and 540 Hz. Still smaller billets, bars, and plates required even higher frequencies that could only be provided by motor generator sets. Popular frequencies for these MG sets were 1, 3, and 10 kHz. In the late 1960s, the development of the thyristor or SCR made practical solid-state power supplies for generating frequencies from 90 Hz to 10 kHz. By the mid-1980s, power transistors became available that made the development of medium- and high-frequency transistORIZED IH power supplies possible.

The decision to use either a thyristorized or transistorized power supply for mass heating depends primarily on the frequency required and on the specific application. Transistorized power supplies are especially cost effective at frequencies of 10 kHz and above. In general, for these frequencies, the transistorized power supplies are much more compact than the equivalent thyristor-type power supplies. Figure 7.57 shows a 1200-kW, 30-kHz transistorized power supply used for heating rods before coiling and quenching to make automotive coil springs. It measures 0.91 m deep × 3 m wide × 2.3 m high (36 in. × 120 in. × 90 in.) and includes the IGBT inverter, load-matching isolation transformer, and load-resonating capacitors. At the time of writing this handbook (2016), both technologies are used at 3 kHz, with SCRs still dominant at the higher power levels.

The power supplies used for most mass heating before forming applications have in common these characteristics:

- Low to medium frequency of operation
- High power
- Continuous duty
- High efficiency and
- Harsh operating environment

As discussed in Chapter 6, selecting the optimum frequency is essential to minimize line length and output temperature differential surface to core. In some very high production applications, use of more than one frequency is required. The system shown in Figure 7.58 for heating steel bars for forming grinding balls uses 1 kHz at the beginning of the line for heating the bars up to the Curie temperature. At this temperature, the steel becomes nonmagnetic and $\delta$ increases dramatically. The remainder of the coil line at the
exit end is powered by 3 kHz to maintain high electrical efficiency. In this system, the bars ranged from 38 to 50 mm (1.5 to 2 in.) in diameter.

Heating before forming requires uniform through heating of the workpiece and therefore demands much higher power than surface heat-treating processes. Heating of small workpieces (Figures 2.18 and 2.28) or small bar end heating systems (Figure 2.22a) may require 100 kW or less at 10 or 30 kHz. However, most forging applications need at least 250 kW, although 1-MW power supplies are also common. Heating of large slabs often requires multiple power supplies each producing many megawatts. One such system, shown in Figures 2.24 and 6.61c, for heating carbon steel slabs (3.2 m/126 in. wide by 0.22 m/8.7 in. thick at 540 tons/h), consists of seven coils each powered by a 6-MW power supply.

Heating of billets, bars, and slabs is most often a continuous process and therefore does not require derating of the power semiconductors as in power supplies for induction heat treating. Continuous operation does mean that all components must be rated to operate at full power for many hours without overheating or degrading performance. It is important to note that water-cooled components stabilize at maximum operating temperature in minutes whereas non–water-cooled components may take hours to reach maximum temperature.

Power supply efficiency is very important in mass heating applications because the cost of electrical energy input is a significant portion of the production process cost [318]. The initial equipment cost is higher when low-loss power circuits and components are provided to increase power supply efficiency. This higher initial cost is offset many times over the life of the equipment by lower energy costs.

The operating environment must always be considered in the design of power supplies. This is especially true in the case of mass heating before forming where conductive dust from scale or die lube is blown through the air and cabinets must be well sealed to prevent this dust from collecting on high-voltage power components. Extremes of temperature are also common especially in cold climates where the lost heat from the heating and forming process is the major source of heat for the facility. The use of antifreeze to cool the power supply and coils may be necessary when the plant is shut down and the temperature is below freezing.

Modern IH systems for forging are designed to minimize the floor space required [654]. The equipment must be at least as long as the heating coil length required to obtain the

FIGURE 7.58
Dual-frequency multicoil induction carbon steel bar heater. (Courtesy of Inductoheat Inc., an Inductotherm Group company.)
desired surface-to-core temperature within the workpiece plus infeed and outfeed mechanisms. The power supply and machine control electronics are usually packaged below the coil line, resulting in a unitized heating system.

In recent years, the ability to accurately computer model the billet and bar heating process has highlighted the advantages of optimizing the power and frequency delivered to each coil in a multicoil system. As discussed in Section 6.3, the temperature profile surface to core plays a major role in the quality of the forging. Minimum coil line length and overall forge system efficiency are features of a well-designed multicoil forge heater.

Forge heating lines with a separate power supply module for each coil combined with a control system that sets the power to each coil have become very popular. The control system takes into account billet or bar material, size, line speed, and other operating conditions to set the power profile that will produce the desired surface-to-core temperature profile. This modular system design also allows a standby function that keeps the billet or bar at temperature during minor line disruptions. Predictive numerical simulation software, such as Inductoheat’s iHaz™, provides the forger the tools to precisely set up the heater to provide bars and billets at the proper forging thermal conditions while optimizing system efficiency. An example of such a system is the Inductoforge® shown in Figure 6.23. This Inductoforge model includes a heating coil shuttle system for rapidly changing coil size to efficiently heat a wider range of billet diameters.

The power modules used in the Inductoforge system are individual power supplies complete with power disconnect switch, rectifier, inverter, control, and load-matching capacitors.

7.9 Special Considerations for IH Power Supplies in Strip Processing Applications

IH of steel strips for galvanizing, galvannealing, galvaluming, annealing, and lower-temperature processes such as paint drying require power supply features most similar to mass heating applications such as forging. As in forging, a large amount of metal (measured in tons per hour) is heated continuously. Here, the heating process is not interrupted to change from one role of strip to the next, or even to change strip thickness or width. Power supply efficiency is also very important because the cost of electricity is a large portion of the total process cost.

Strip heating differs from forging by the thickness of the workpiece that is heated. Where forging involves heating of billets, bars, or rods of relatively thick cross section, in strip heating, the workpiece thickness is measured in thousandths of an inch or fractions of a millimeter. This requires application of a much higher frequency to obtain acceptable heating efficiency. In most cases, frequencies from 30 to 150 kHz are used.

IH power supplies used for strip heating applications have in common these characteristics:

- Medium to high-frequency of operation
- High power
- Continuous duty
- High efficiency
- Unusual and often harsh operating environment
In some strip heating applications, including organic coating and paint drying, the strip is conveyed horizontally as shown in Figure 4.128b. Here, the power supply is adjacent to the heating coil and connected by a short, wide, horizontal bus to minimize voltage drop and power loss.

Induction galvannealing on the other hand is accomplished by passing the strip through a pot of molten zinc and then vertically through one or more heating coils located on a gantry high above the factory floor [655]. As shown in Figure 6.72b, the coil and high-frequency inverter portion of the power supply are suspended from a movable gantry. The DC rectifier and control portion of the power supply are located conveniently on the factory floor and connected to the 100-kHz high-frequency inverter by low-loss cables that carry only DC. This is obviously an application-specific design devised to meet the demanding physical requirements of the system while maximizing efficiency and maintainability. A module containing the high-frequency transistorized inverter, heating coil, and interconnecting bus may be located directly above the pot of molten zinc and is therefore exposed to high ambient temperatures and electrically conductive zinc dust. In some installations, this module is completely enclosed and air-conditioned to provide a friendlier environment for both the IH equipment and maintenance technicians.

### 7.10 Simultaneous Dual-Frequency Power Supplies

The most obvious application to take advantage of simultaneous heating with two significantly different frequencies is gear hardening. As explained in Section 4.9.1.3.2, application of a relatively low frequency heats the root of the gear tooth while high frequency heats the surface and tip of the tooth. The appropriate application of both frequencies simultaneously results in a hardness pattern of uniform depth that follows the contour of the gear surface.

A number of power supply configurations have been developed to provide 10 kHz or below and 100- to 400-kHz simultaneous or quasi-simultaneous power to a workpiece.

#### 7.10.1 Dual Inverter

The most basic dual-frequency power supply consists of two inverters, one for generation of medium frequency and one for high frequency. These can be housed in a single cabinet and utilize a common rectifier section to supply both inverters or can consist of two standard “off the shelf” power supplies. The output of the low-frequency inverter is inductively connected to the heating coil to pass the medium-frequency current while rejecting the high frequency provided by the high-frequency power supply. The output of the high-frequency inverter is capacitively connected to the heating coil to pass the high-frequency current while blocking the medium frequency of the medium-frequency power supply. Power control is simply accomplished by setting the power desired from each inverter. Figure 4.190 shows typical heating coil current and voltage waveshapes.

As an example, Figure 4.191a shows Inductoheat’s machine configured for induction hardening of an internal wide-face gear-like component, having a minor gear diameter of 176 mm and a major gear diameter of 186 mm using single-shot simultaneous dual-frequency heating. The total power exceeds 1200 kW, comprising medium-frequency (10 kHz) and high-frequency (120–400 kHz) modules working not just simultaneously, but in any sequence required to optimize the properties of heat-treated gears.
7.10.2 Single Inverter

The single full-bridge inverter is switched at the desired high frequency and switching is asymmetrically modulated at the desired medium frequency [638]. The resulting inverter output containing both high- and medium-frequency components is connected to the heating coil by an impedance matching filter network. The filter is designed to pass only the high “switching” frequency and the medium-frequency “modulation” that is generated by the asymmetrical switching of the inverter bridge. High-frequency to medium-frequency power ratio control is accomplished by adjustment of inverter bridge switching frequency and the level of low-frequency asymmetrical modulation.

7.10.3 Duty Ratio Inverter

A single inverter capable of operation at both the low and high frequencies is connected to the heating coil by an impedance matching filter network that will pass current at either the low or high frequency. Figure 7.59 shows the frequency response of such a filter network designed for operation at 10 and 200 kHz.

The quasi-simultaneous dual frequency is accomplished by rapidly switching the inverter between low frequency and high frequency during the heating cycle. This approach provides the desired dual-frequency heating if the switching between frequencies occurs several times during the usually very short heating cycle. The relative power, low frequency to high frequency, can be controlled by the percentage of time of each frequency or “duty ratio.” The typical coil voltage and current are shown in Figure 7.60.

![FIGURE 7.59](image)

Example of the frequency response of a filter network designed for operation at 10 and 200 kHz.

![FIGURE 7.60](image)

Duty ratio coil current and voltage waveshapes.
7.10.4 Dual Coupled Solenoid/C-Core

Another method of providing dual-frequency heating, as disclosed in US Patent No. 7,253,381 B2, employs two power supplies and two methods of coupling energy to the workpiece. High-frequency power is applied to an induction coil that surrounds the workpiece so that a high-frequency magnetic field couples with the workpiece to inductively heat the workpiece. A C-core inductor, as described in Section 6.9.2.5, is coupled to a coil that has low- or medium-frequency power applied to it. The workpiece is inserted in a gap in the C-core inductor magnetic circuit so that it experiences low- or medium-frequency heating when low-frequency current is applied to the coil coupled with the C-core inductor. The workpiece may be inserted around the C-core if the workpiece has an opening. Since separate power supplies are used, the power at each frequency may be applied simultaneously, individually, or sequentially as required by the hardening process.

7.11 Inverters with Independent Frequency and Power Control

A most versatile IH power supply with independent frequency and power control does not have a resonant or power factor corrected output load circuit. This means that load matching is simplified because it is only necessary to select an output transformer ratio that will match the impedance of the heating coil to the inverter. It also means that without a resonant capacitor, the inverter must provide the full kilovolt-ampere of the heating coil, which makes this design particularly well suited to low Q applications such as scan and single-shot hardening.

The Inductoheat Statitron IFP shown in Figure 4.68b combines the Independent Frequency and Power control inverter with a general-purpose scan hardening machine. The IFP inverter in this system has the ability to simultaneously change power output between 0 and 160 kW and frequency from 5 to 60 kHz on-demand. Seamlessly altering frequency and power output allows the operator to achieve differing case depths during a continuous heat-treating cycle. This revolutionary capability allows for the heat treatment of a variety of part shapes with a single coil design [645].

The patented design of the Statitron® IFP™ power supply eliminates the need to perform changeovers for varying part features and processes, while eliminating load matching when changing frequencies. This permits the operator to use a single coil for hardening and tempering processes by automatically adjusting both output frequency and power.

7.12 Power Supply Cooling

Water cooling is the most common method used to remove the heat generated by losses in the IH power supply, the output bus bars or cables, and the induction coil. The water quality, temperature, flow rate, and other requirement vary depending on the type of power supply and the application [656–658].
7.12.1 Water Quality

In vacuum tube oscillators and power supplies using SCRs, there is DC voltage potential between the water-cooled power components. This DC potential between components can cause leakage current to flow through the water in the hose connecting them. If not controlled to acceptably low levels, this current can cause electrolysis. Electrolysis over time will eat away the metal at one end of the water circuit causing a water leak. The metal eaten away from one end will try to deposit at the other end of the water circuit. The deposited material can form a blockage of the water circuit causing an overheating fault or component failure owing to insufficient cooling. To protect against these modes of failure, the leakage current must be controlled by limiting the conductivity of the water or by providing sufficient hose length between components at differing DC potential. The conductivity of the water used to cool vacuum tube oscillators and power supplies using SCRs with short interconnecting hoses is typically limited to a maximum of 40 micromhos. This requires that the water be distilled and deionized. The maximum conductivity can be raised 10 times to 400 micromhos where the interconnecting hose length is sufficient to limit the DC voltage potential to less than 20 V/ft. This means 40 ft of hose must be used to connect across a DC bus potential of 700 V.

Modern transistorized power supplies are usually designed to avoid direct contact between the cooling water and any DC voltage potential. This eliminates the possibility of damage caused by electrolysis. In this case, water with high conductivity, even filtered quenchant, can be used to cool the power supply. This approach has been very successfully used in Inductoheat’s high- and medium-frequency power supplies. The HSP (heat station power supply) and UP12 (Unipower 12), which are often part of a unitized heat-treating machine, have been in service since 1994, successfully using quench for cooling.

7.12.2 Cooling Water Flow Rate

The individual water-cooling circuits within the power supply are designed to provide the flow rate required to cool the various individual power components on the circuit. Components requiring the coolest water such as capacitors and power semiconductor heat sinks are placed close to the inlet, and bus bars and inductors that can tolerate higher temperatures are placed near the outlet end of the circuit.

Some circuits require much higher flow than others do because some components have higher power dissipation or are unable to tolerate significant temperature rise from inlet to outlet. The typical flow rate per circuit within the power supply is approximately 2 to 3 gpm (gallons per minute). Obviously, large power supplies will have more cooling circuits and therefore higher flow requirements than smaller power supplies. All the individual water circuits within the power supply are connected in parallel from inlet to outlet manifolds and the pressure inlet to outlet must be sufficient to guarantee the engineered flow rate. This pressure is usually specified to be a minimum of 25 or 30 psi and is usually monitored by a minimum pressure differential switch.

7.12.3 Cooling Water Recirculating Systems

Most power supplies are cooled by closed-loop water recirculating systems. These systems have a pump, heat exchanger, temperature control valve, tank, filter or strainer, and plumbing to interconnect all the components. Tables 7.3 and 7.4 show rating data applicable to these water-cooling systems.
7.12.3.1 Pumps

Most water recirculating systems are designed with centrifugal pumps. These pumps have well-defined pressure versus flow performance characteristics. Knowing where a pump is expected to operate is essential in sizing the system. The total water flow required must include the power supply, external bus or water-cooled cables, the heat station (if separate from the power supply), the inductor coil, and any other external components that are cooled by the system. The pressure required from the pump must include the drops across the power supply and other components and also the pressure drop across the supply and return lines.

7.12.3.2 Heat Exchanger

The second item of importance in the recirculation system is the heat exchanger. Most systems use a water-to-water heat exchanger. Typically, modern systems are using plate-type heat exchangers that are compact and can be assembled from standard plates to provide the necessary capacity.

Most IH power supplies are designed to operate with a maximum inlet water temperature of 95°F (35°C). To properly size the heat exchanger, one must know the power dissipated in kilowatts or heat load in British thermal units per hour (BTU/hr), the flow rate, and the “lead,” which is the difference between the coolest water on one side of the heat exchanger and the coolest water on the other side. The lead has a major impact on the size of the heat exchanger. A lead of 10°F is common, which requires that the plant-side water temperature be 85°F, or less.

An example showing the power losses in a typical IH system is given in Figure 7.61. As shown, an IH system with a power supply operating at 100 kW output and 90% efficiency will have 10-kW losses. The matching station and interconnecting bus with 85% efficiency will lose 15 kW, and the load coil with 70% efficiency will lose 25 kW. Thus, the total power losses are 10 kW + 15 kW + 25 kW = 50 kW. If the part is heated for 10 s and the entire cycle is 40 s, the duty cycle is 10/40 or 0.25. The heat load of the cooling system is then 50 kW × 0.25 = 12.5 kW. To convert 12.5 kW to British thermal units per hour, multiply it by 3415 and the heat load is then 42,688 BTU/h.
The flow of 85°F water required to cool the above system using a well-designed heat exchanger can be calculated using the following:

\[
\text{Flow (gpm)} = \frac{\text{Heat Load (BTU/hr)}}{500 \times \text{Temperature Rise (°F)}} = \frac{42,688}{500 \times 10} = 8.5 \text{ gpm.}
\]

It is important to note that the worst-case operating conditions for the system should be used in sizing the water-cooling system. For example, if it is possible that the duty cycle in the above system could be 0.5 for another application, the flow required would double to 17 gpm.

### 7.12.4 Common Water-Cooling Problems

Some of the most common problems associated with power supply cooling systems are outlined below.

1. Supply and return lines to and from the power supply are too small and introduce excessive pressure drop, leaving too little differential across the power supply.
2. The cooling system is undersized for the application because the process is less efficient or has a higher duty cycle than the originally anticipated.
3. Filter or strainer has high pressure drop and needs cleaning or replacement.
4. Incorrect flow due to changes made to the water circuit connections during maintenance.
5. Heat exchanger efficiency poor or restricting flow and needs cleaning.
6. Ambient temperature and relative humidity too high and therefore cooling water temperature is too high.
7. Recirculating cooling water is too cold, causing moisture condensation on high-voltage components.

![Diagram of Power Supply](image-url)
7.13 Process Control, Monitoring, and Quality Assurance

7.13.1 Prelude to Discussion of Process Control and Monitoring

Although typical automotive heat treating specifications (e.g., AIAG Specification CQI-9) continue to require destructive testing of parts to verify the heat-treating process, the use of appropriate systems to monitor all significant variables in the process can lead to a substantial reduction in the number of parts that must be cut in order to verify a continuously running process [659].

One of the most important features of a modern IH machine is the ability to effectively control and monitor the significant process variables. The control system should allow presetting a number of system input parameters with the expectation that, via a specified control algorithm, process variables will be controlled within certain values, with the final result being the production of the desired system output, a properly processed part. The monitoring system must be independent of the control system and should provide the operator with information about what is actually happening during the process. It should indicate whether the parameter values measured are essentially the same as the values used and recorded for a test piece that is known to be properly processed. If the values are the same, or within acceptable limits, it may be inferred that the processing of the workpiece has been successfully completed to replicate the properly processed part [660,661].

The features of a control and monitoring system are largely dependent on the process being monitored and controlled. A heat-treating process (i.e., surface hardening) is very different from a mass heating process (i.e., heating before hot forming or coating). The desired parameters to control in heat treating are the microstructure, hardness profile, and magnitude and distribution of residual stresses within the finished part, just to name a few. These are controlled in order to produce certain desired mechanical properties of the part, which include wear resistance, tensile strength, fatigue strength, and ductility. The final properties are generally the result of two stages of processing, which include a hardening and a tempering/stress-relieving cycle. Even the time between these cycles can be an area of concern.

In a mass heating process, the main parameter to control is the final temperature distribution and, in some cases, transient temperature gradients. The final temperature distribution is controlled in order to provide a workpiece that is easily formed as in a forging, rolling, or extrusion system, or coated with another material such as galvanizing, galvannealing, or paint curing.

The comparison of the main differences between typical metal heat treating and mass heating processes is provided in Table 7.5. The differences, as stated above, are many. Therefore, the description of control and monitoring techniques is broken into two areas, heat treating and mass heating.

It should be noted that, in either case, the controllable parameters and those that are monitored during the process are not the desired final characteristic of the part being processed, but intermediate variables that can affect the final characteristics of the part being processed. For instance, wear resistance, tensile strength, fatigue strength, and ductility are not measured with the monitoring system, but such variables as power level, frequency, scan speed, part positioning, quench temperature, quench flow, and so on can all have a material effect on the final outcome of the processing operation, the characteristics of the finished part.
7.13.1.1 Specifics of Control and Monitoring of Induction Heat Treating

As described in Chapters 3 and 4, the induction metal heat-treating process is a complex combination of electromagnetic, heat transfer, and metallurgical phenomena. Two of the most common applications of induction heat treatment are surface hardening and through hardening. Both applications involve heating the workpiece to the austenizing temperature, holding it at temperature for a period long enough for completion of the formation of austenite, and then rapidly quenching the steel, cast iron, or powder metallurgy component to produce a very hard but brittle structure called martensite.

A subsequent but no less important step in the process is the tempering of the hardened material to relieve internal stresses and improve toughness and ductility.

During the heating of the workpiece for hardening, significant metallurgical changes take place. These are covered in detail in Sections 4.1.1 and 4.1.2, but a brief review will help understand the requirements of the control and monitoring system.

For a workpiece made from steel or cast iron, the metal goes through a change in crystalline structure when it is raised to a specific critical temperature resulting in a material called austenite (Figure 4.4). The material must then be quenched rapidly enough to cause a change again in the crystalline structure to a material called martensite (Figure 4.7). The required transformation temperature for a particular alloy and hardness attained are a function of the material chemical composition, degree of austenitization, intensity of quenching, and prior microstructure (see Section 4.1).

In looking at the time–temperature isothermal transformation diagrams and continuous cooling diagrams for a typical material (Figure 4.7), it is apparent that if the
material is cooled more slowly than the time necessary to miss the nose of the transformation curve, the softer structure will be obtained, which might not provide the required properties. It should be mentioned here that in the field of fast heating, the critical temperatures of phase transformation (e.g., \( A_{c1} \) and \( A_{c3} \)) might be noticeably shifted (Figure 4.28).

Proper control of heat treating involves not only heating the workpiece but also taking the necessary steps to ensure that proper cooling conditions have taken place within the required period.

Many heat-treating systems require relatively close coupling coil-to-workpiece gaps. In some cases, the development of the proper heat-treating pattern requires the ability to precisely spin or move the workpiece at a specified rate while turning the high-frequency power ON and OFF to harden specific sections of the workpiece while leaving others unaffected. The inductors are relatively delicate devices and protective circuitry must be incorporated to ensure that travel is immediately stopped if a workpiece touches the inductor or traveled too close to its proximity.

In order to properly harden the workpiece, it is also necessary to quench it properly. A specific minimum quench volume is required during a specific time interval. The quench medium must have the appropriate cooling curve and be of the correct concentration to bring about the proper heat transfer.

In some cases, the alloy may be properly heated but can only be quenched effectively to a certain depth within the workpiece because of the thermal properties and hardenability of the material used. Hardenability curves are useful in determining what hardness can be produced with a given material at a specified depth inside the workpiece (Figure 4.24). The workpiece material must have sufficient hardenability in order to develop the prescribed hardness pattern to the required depth.

In selective hardening applications, power produced must often be concentrated along certain sections of the workpiece, which requires the use of laminations or other types of magnetic flux concentrators, whose position and characteristics are critical to the hardening process.

The final step in many heat-treating processes is tempering or stress relieving. It requires the desired areas of the workpiece to be raised above certain minimum temperature for a specific length of time. This typically decreases the hardness to some extent, producing a reasonable compromise among the hardness, toughness, and ductility.

Each phase of the process, heating, quenching, and tempering, must be precisely controlled and monitored in order to produce a properly heat-treated part. Although the process may be successfully done with a minimum of monitoring equipment, safety and liability concerns force manufacturers to invest in systems that will document that they have done everything possible to appropriately control the process. In addition, every effort must be made to detect and remove defective parts before they reach the point of assembly in a critical subassembly.

### 7.13.1.2 Specifics of Control and Monitoring of Induction Mass Heating

In a typical mass heating system (i.e., inline bar, billet, slab, or strip heating applications), the applied level of power is turned on continuously at the selected frequency as the part traverses through a coil having relatively generous air gaps compared to the majority of heating-treating applications. In most cases, there is no rotation of the part required. This may seem like a relatively simple process in concept; however, the practical implementation requires much experience and technical foresight.
Materials are sometimes heated very close to the melting temperature. Much higher voltages are utilized on the multiturn coils, which can lead to problems with arcing, corona discharge, ground loops, and personnel safety hazards. Arriving at a stable process can sometimes be a challenge since a cold load (that occurs, e.g., during the startup and shutdown stage), a hot load, and a continuously running load all require different power supply tuning to optimize performance.

The requirement for a specific distribution of temperature within the workpiece necessitates careful selection of frequency, power, and line length. Convection, conduction, and radiation losses must be carefully assessed to ensure that the system will provide the required thermal specification. Improperly heated workpieces can cause major problems during the forging, hammering, or forming process.

Handling metal that is heated to forging temperatures can be challenging. Expansion of components in proximity to the hot metal and scale can cause mechanical problems. Personnel protection is a primary concern. Preventing damage to expensive equipment is an important secondary concern.

7.13.2 Meters and Meter Circuits

The task of measuring the wide variety of parameters seen in an induction heat-treating or mass heating applications can be a challenge. For many years, it was possible to use simple analog d’Arsonval meters to measure most waveforms that might be seen in industrial power equipment. These meters utilize a permanent magnet and a vane or indicator that is mounted with a small coil of wire to a metal pin that allows the vane and coil assembly to rotate freely. When a DC is passed through the coil of wire, the vane rotates or moves to indicate the magnitude of the current. For DC signals, this type of meter provides a quickly responding visual indication of the value of the DC voltage or current being measured. AC voltage or current is measured by first rectifying the signal and then measuring the DC value of the rectified signal. This assumes that the AC signal is a perfect sine wave. A reading that may be referred to on the meter scale as root mean square (rms) is actually an average reading of the waveform with the meter scale multiplied to give the rms value assuming that the waveform is a sine wave.

Analog meters, on the other hand, are not always adequate to measure the waveforms that may occur at the output of a power supply. The waveforms are of higher frequency and may involve square waves or combinations of sine waves and pulses at different frequencies. The voltages may be relatively high, in the range of 2000 V or even more. Internal to the power supply, there may be triangular waves or pulses at different frequencies.

Certain types of analog meters are built with internal mercury switches that allow setting a pointer at a certain place on the meter scale. When the reading of the meter goes beyond the set point, the switch closes to indicate that the meter is reading above a minimum set point. On dual set point meters, a range can be set with one switch at the lowest acceptable reading and another switch at the highest acceptable reading. This type of meter would then allow the relay circuits to be interrogated to ensure that the meter reads above the lower set point and below the upper set point.

An alternative to the simple analog meter is a digital meter that is designed to give the actual rms value of a given waveform. These meters utilize special integrated circuits that will provide a DC output proportional to the true rms value of the waveform within certain limits. Used within their rating, these meters provide a very accurate measurement of the magnitude of the power supply waveshapes. The major problem with using the digital meters is that it often takes several seconds for the meter to respond with a correct reading. This can be a problem because there are many applications where the heating time is
less than the meter response time and it is not possible to get a correct reading during the machine cycle. Some manufacturers have responded to this problem by providing both a quickly responding bar graph as well as the slowly responding digital readout of the value of the parameter, in the same meter housing.

Without much regard to the type of waveform being measured, some early techniques for measuring process parameters were as simple as a dual set point meter that would indicate if the parameter dropped out of the acceptable range during the cycle. On less critical variables, this approach can still be the most prudent way to design the system. This approach is often used on programmable logic controller (PLC) systems with the analog readout being internal to the PLC rather than on a discrete meter.

This approach involves the design of an interrogation circuit in the machine control to check the variable during the time that it should be in the normal operating range. For such variables as flow rate and temperature, this involves the designer’s best guess as to the time it may take for the flow or temperature to stabilize before making an accept/reject measurement.

### 7.13.3 Features of Control/Monitoring Strategies for Induction Heat Treating versus Induction Mass Heating

In terms of monitoring different types of processes, the approaches would be significantly different. Possible guidelines for development of control and monitoring strategies are outlined below for induction heat treating and induction mass heating applications.

#### 7.13.3.1 Induction Heat Treating

As described above, there are many variables in the induction heat-treating process, but some are more important than others in terms of assuring consistent results.

A list of variables for the induction heat-treating process would include the following:

1. Material chemical composition, prior structure, and properties
2. Workpiece geometry
3. Induction coil geometry
4. Part-to-inductor positioning
5. Frequency
6. Active power, voltage, current, and kilovolt-ampere
7. Heat time
8. Quench medium, temperature, purity, concentration, flow, and pressure
9. Quench delay time (if required)
10. Incoming part temperature
11. Magnitude and a distribution of temperature after the heat cycle
12. Workpiece thermal condition after quenching
13. Inductor and bus network temperature
14. Power component and heat station temperature
15. Incoming line voltage
16. Rotation
17. Scan speed
As described in Chapter 3, the resistivity, thermal conductivity, specific heat, and relative magnetic permeability of the workpiece all change with temperature. Magnetic permeability is also affected by the magnetic field intensity used for heating the part. At first glance, the changes in these parameters may appear to be very dramatic, but there are some factors that may mask the expected effect to a large extent. For hardening applications often running at 10 kW/in.², the change in relative magnetic permeability may often be only from 9 to 1 (Figures 3.8a, 3.9 and 3.10). Because the current penetration depth varies as the inverse square root of $\mu_r$ changes (Equations 3.6 and 3.7), the actual change in inductance from a cold to a hot load may be relatively small. Sample calculations in Figure 7.62 illustrate this point.

As shown in Figure 7.62, the actual change in inductance and impedance from a cold load to a hot load is relatively small and is greatly reduced for higher power densities. The most interesting parameters from the standpoint of monitoring equipment would be the coil current, the energy input, and the system power factor. Even these will give only a partial picture of the subtleties of the IH process because the quenching and tempering phases are as critical. With this in mind, it would be desirable for the end user to have equipment available that could monitor several parameters simultaneously in real time and indicate which parameters may potentially cause an improperly heated treated part.

Some manufacturers carry out a design of experiments before purchasing equipment. In this way, it is possible to determine the most significant variables in the process. The equipment design may then focus on controlling these parameters rather than the larger number of less significant variables that could be pursued.

Either computer modeling, past experience, or a design of experiments approach may be used to select the most important variables to monitor and control during the heat treating. Some variables are more consistent than others and can be monitored with very inexpensive circuitry. Others are critical with respect to their magnitude and timing relative to other parameters and more expense may be justified to ensure that these variables are more tightly monitored and controlled. The items in the preceding list of variables may be broken down as shown below for a given machine.

**Simple Inexpensive Check or Check Seldom Required**

1. Material chemistry and prior structure
2. Workpiece geometry and tolerances
3. Induction coil geometry
4. Induction coil material and magnetic flux concentrator (if applied)
5. Part-to-coil location

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Power density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>Low (about 1 kW/in.²)</td>
</tr>
<tr>
<td></td>
<td>High (about 10 kW/in.²)</td>
</tr>
<tr>
<td>Resistance</td>
<td>$-27%$</td>
</tr>
<tr>
<td></td>
<td>$-10%$</td>
</tr>
<tr>
<td>Impedance</td>
<td>$-81%$</td>
</tr>
<tr>
<td></td>
<td>$-65%$</td>
</tr>
<tr>
<td>Current</td>
<td>$-36%$</td>
</tr>
<tr>
<td></td>
<td>$-15%$</td>
</tr>
<tr>
<td>Power factor</td>
<td>$+132%$</td>
</tr>
<tr>
<td></td>
<td>$+66%$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$-53%$</td>
</tr>
<tr>
<td></td>
<td>$-57%$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$-20%$</td>
</tr>
<tr>
<td></td>
<td>$-16%$</td>
</tr>
</tbody>
</table>

**FIGURE 7.62**
Sample calculation results of actual change percentage of the process parameters when part has been heated from a “cold” stage to a “hot” stage for low power density (heating before hot forming) and high power density (surface hardening).
6. Quench medium, temperature, purity, concentration, and pressure
7. Incoming part temperature
8. Part temperature after heat
9. Part temperature after quench
10. Inductor and bus temperature
11. Power component and heat station temperature
12. Incoming line voltage

**More Expensive Monitor May Be Justified**
1. Frequency
2. Power, voltage, current, or kilovolt-ampere
3. Heat time
4. Quench flow
5. Part temperature during heat
6. Part rotation
7. Scan speed

A heat-treating system would require signature monitoring of the energy envelope during hardening and tempering. Quench timing, volume, and temperature would typically be monitored. Final part temperature during the heating and tempering may also be monitored. If there is a concern for material growth during heating, strain gauges may be installed in tooling to measure force or percent elongation. This process could require up to 16 or more parameters to be monitored on a signature-type system to ensure correct magnitude and timing of all critical parameters.

### 7.13.3.2 Induction Mass Heating

For the mass heating, there is little concern with timing conditions or turning the power supply ON and OFF except in cases of attempting to maintain line temperature for a short time during equipment malfunction. Exit temperature is an important parameter and often is measured with a dual set point optical pyrometer improving reliability and accuracy of temperature measurement. In order to prevent overheating the workpiece in the event of a slowdown or stoppage in part motion, in continuous heating applications, a stop motion detector is usually required. On reheating applications, it is sometimes necessary to sense the incoming part temperature and reset the power supply output power and a process recipe to compensate for variations in the incoming temperature. Variations in part emissivity may require a special two-color pyrometer to better evaluate the incoming temperature and subsequent power settings required.

With certain types of material, rapid heating can cause cracking of the part during heating (e.g., IH of high carbon content billets and bars to forging temperatures or induction hardening of gray irons). For these materials, a slow ramp up may be required in the application of power to the workpiece.

In cases of using continuous heating modes, there is little need to monitor the energy in short intervals. Total power consumption and cost of electrical power are major concerns and often warrant the installation of analog or digital watt-hour meters.
A list of variables for the induction mass heating process would include the following:

1. Material chemical composition and properties
2. Material geometry
3. Induction coil geometry
4. Induction coil material
5. Part-to-coil relative size
6. Frequency
7. Power, voltage, current, or kilovolt-ampere
8. Heat time
9. Incoming part temperature
10. Part temperature after heat and temperature uniformity
11. Inductor and bus temperature
12. Power component and heat station temperature
13. Incoming line voltage
14. Production rate

As in the case of induction heat treating, some variables are more consistent than others and can be monitored with inexpensive circuitry. Others are critical and more expense may be justified to ensure that these variables are more tightly monitored and controlled. These items may be broken down as shown below for a given machine.

**Simple Inexpensive Check or Less Frequent Check Required**

1. Material chemical composition and properties
2. Material geometry
3. Induction coil geometry
4. Induction coil material
5. Part-to-coil location
6. Incoming part temperature,
7. Inductor and bus temperature
8. Power component and heat station temperature
9. Incoming line voltage

**More Expensive Monitor May Be Justified**

1. Frequency
2. Power, voltage, current, or kilovolt-ampere
3. Heat time
4. Part temperature
5. Part “stop motion”
6. Production rate
In short, there is no single answer for monitoring and controlling an induction heat treating or mass heating system. Each application is different and requires careful analysis of the process requirements and sensitivity of the process to variation in ambient conditions and input parameters.

7.13.4 Basic Principles of Feedback and Control Algorithms

Modern control/monitoring systems utilize state-of-the-art communication techniques to ensure reliable operation of induction machinery. A variety of control algorithms are available in order to properly control a power supply or the output of an IH system. These may be composed of open- and closed-loop control systems to accomplish the control of material transport, output power, and temperature.

The basic elements of a process control system are shown in Figure 7.63. A set point is applied to the system as the input at the summing point or feedback comparator. In a closed-loop system, the final controlled variable is measured and a signal proportional to its value is returned to the comparator. If the value is below the desired output value, the difference between the input signal and the control signal, or the system error signal, is fed into the final control element. The final control element then increases the value of the controlled variable until the error signal approaches zero and the value of the controlled variable approaches the ideal or desired value. This comparison and response of the system can be handled in a variety of ways that are described below.

7.13.4.1 Open-Loop Systems (Feedforward Control Systems)

A true open-loop system would run without feedback by simply setting an input variable and allowing the output variable to fluctuate within an acceptable range without feeding back any indication of magnitude, phase, frequency, temperature, and so on. A simple water valve might be an example of a completely open-loop system. If the valve is opened, the fluid may flow in the system from one point to another. If system pressure changes for some reason, the flow in the circuit may change because there is no feedback to automatically adjust the system input to compensate for changes in the output variable. Some open-loop systems do measure an output variable but use it for registration purposes only.

Many open-loop systems are combinations of closed-loop components that provide a regulated input variable to the system but provide no measurement or feedback of the final critical system output variable. For example, an IH power supply may use regulation circuits to provide a very stable input power to the heating coils, whereas no measurement is made of the final exit temperature of the part. The system is running essentially open-loop

![Basic feedback control system](image-url)
with the assumption that stable input will provide stable output. A typical rotation motor drive would also be used in this fashion. The drive itself may utilize IR compensation to regulate the voltage to the motor armature but there is no measurement of the actual speed of rotation of the motor or any attempt to correct it to a desired value. The assumption is that once it is set, it will remain the same for each cycle to be run.

One example of an effective use of an open-loop system would be wire and cable heating systems where it is very difficult to reliably measure the output parameter.

### 7.13.4.2 Closed-Loop Systems (Feedback Control Systems)

Obviously, if we are really concerned about arriving at the right value for the controlled output variable, it pays to measure it and to use it as a signal to stabilize the control response to make sure that the measured value is the desired value. This may be done on an IH system by measuring the part temperature and adjusting the controller response based on the difference between the actual measured temperature and the desired temperature. Once this measurement is made, there are several common ways of using the error signal to change the value of the controlled output variable.

### 7.13.4.3 ON–OFF Control Algorithms

An ON–OFF control has two states. It is either fully ON or fully OFF. There is no intermediate state. If the value of the controlled output variable is below the lower set point, the error signal will drive the control to turn fully ON, providing maximum power to the system until the value of the controlled output variable exceeds the upper set point (Figure 7.64). With this type of control, the value of the output variable will oscillate about the desired value with the rate of oscillation dependent on the system time response and the upper and lower set point levels.

This sounds simple but can be problematic when trying to make small corrections. Unless an appropriate amount of hysteresis (control response delay) is added to the circuit, frequent ON–OFF cycling and hunting or oscillation of the supposedly controlled output variable can occur. This type of system works best when there is a relatively long time delay in system response.

![Figure 7.64](image-url)  
Simple ON/OFF control.
7.13.4.4 P, I, D, PI, and PID Control Algorithms

A more sophisticated way of approaching the control on a system would be to implement proportional (P), integral (I), and derivative (D) types of control. These may be implemented individually or together depending on the specific application requirement.

a. Proportional Control. *Proportional control* is a term used to describe a control circuit that provides full controller output below a specified level. Above that level, the controller response to an error signal is diminished as the controlled output variable approaches the desired value. A proportional band is specified above and below the final desired value for the controlled output variable. When the controlled output variable is operating within the band, a proportionally smaller response occurs to an error signal. The normal setup that is needed for a proportional-type controller would be the manual reset and the gain (or bandwidth) setting.

The manual reset will change the position of the proportional band with respect to the set point to apply more or less output correction in response to an error signal when the value of the controlled output variable is near the set point. An incorrect value for this setting will result in the actual value of the controlled output variable being more or less than the desired value.

The gain (or bandwidth) setting has to do with setting the level or amount of controller response to an error signal when the value of the controlled output variable reaches a specified percentage of the set point. Too low a value for the gain setting will result in droop error, or the actual value of the controlled output variable being less than the desired value. Too high a value for the gain setting will result in oscillation of the controlled output variable.

Proportional controllers are most useful where the process is relatively stable and the set point is not often changed.

b. Integral Control. In the proportional mode, the controller provides a response based on the value of the error at a specific time. The integral feature is used with the proportional mode to provide a response signal in proportion to the previous history of the error signal. The response is based on the net area under the error curve and the response signal may be set by the integral gain setting to be equal to a proportion of the area under the error curve. The net effect is to allow the value of the controlled output variable to “home in” on the set point level over time.

c. Derivative Control. With the derivative mode of control, the response is based on the “time rate of change” of the error signal. If the error is negligibly small but is changing rapidly at that time, the derivative control portion of the system will apply a relatively large correction. The derivative mode of control by itself is inherently unstable and is always used in combination with other types of control.

The most common combinations of these control modes would be proportional–integral (PI), proportional–derivative (PD), and proportional–integral–derivative (PID). Transfer functions for the various modes may be found in standard textbooks on process control [662,663].

The response of these control modes can be set up to be either direct or reverse acting. This means that the response to the error signal for a direct-acting system would be to increase system output when the error increases. Most often, for temperature control, a
reverse-acting system is required so that if the temperature is too high, the kilowatt output to the load circuit is reduced.

7.13.4.5 PLC Controller

With the advent of the PLC, a large number of points could be monitored in real time during the heat treatment cycle. PLCs are used for controlling machine functions through ladder logic and a variety of analog and digital output modules and servomotor drives. Often a separate controller would be used for specific PID loop functions within the IH system. PLCs are commonly used in an open-loop fashion for the heating portion of the system. An analog input signal is provided from the PLC to the power supply. The controlled output variable from the power supply would be the kilowatt level. This is often measured at the PLC and an alarm circuit may be set to indicate if the actual and preset values do not correspond to each other but there is no attempt to reset the analog input to the power supply based on the measured kilowatts.

Most PLC systems utilize the PLC for control as well as fault and diagnostic messaging and a separate computer-based system that may be used for signature-type monitoring of the process in real-time. A more modern example of a system that is able to do the control, data acquisition, and signature monitoring in one package is the Inductoscan® system from Inductoheat, which utilizes a computerized front end with human–machine interface (HMI) coupled with a PLC control in order to provide the best of both worlds.

7.13.4.6 Controller Tuning

Ideally, when a controller is set up for operation on an IH system, the desire is to get the workpiece up to the required temperature as quickly as possible with very little overshoot. This same objective is held for a motor drive or positioning system. The goal is to move to position at a preset velocity and to arrive exactly at the chosen end point. A servo positioning system is easily able to accomplish this task.

On induction mass heating systems, there is a considerable lag from the time an input signal is applied until the temperature of the part is stabilized. Coil lines may exceed 10 m long (Figure 6.12). It may take minutes for a part to traverse from one end of the line to the other. It is necessary to measure the response to a given change before attempting to make another change in the system's input parameters. Many systems that are envisioned to be a PID system to control the part temperature are actually running with the gain, reset, and proportional band settings adjusted to such a slow response that the system functions as an open-loop system. In the area of induction hardening, the cycles are much shorter and there is more likelihood of being able to accomplish closed-loop control.

For either type of system, the general approach would be to attempt to use standard off-the-shelf controllers and tune them up on the production floor. This can become time-consuming and costly, so their use must be carefully reviewed to determine whether the benefits outweigh the additional cost associated with the control components and implementation costs.

7.13.5 Energy Monitoring

An energy monitor available from Inductoheat measures and displays the actual energy delivered to the induction coil in kilowatt seconds. It is a relatively inexpensive device. Once a heating pattern is developed and the appropriate recipe (including power and heating
time) is established, this information is preset into the monitor. The user then enters the acceptable lower and upper kilowatt second limits. If insufficient or excessive energy is applied to the load, the display will show “REJECT/UNDER” or “REJECT/OVER,” respectively. Auxiliary contacts can be used to reject the part in automated lines or sound an alarm in manual operations. If the count falls within the preset range, the “ACCEPTABLE” indicator will be displayed. The energy monitor can be used as an induction process controller to turn off the power automatically when the desired amount of energy is delivered to the load. The energy monitor circuitry accurately measures and displays the output of the power supply. Although earlier RF monitoring was done on the input line, fiber optics now make it possible to monitor the high voltages and frequencies on the output safely.

There is often debate with respect to the best location to monitor the voltage and current for the energy monitor. Ideally this should be done at the coil terminals to eliminate other components from masking energy changes or causing false indications of changes. The energy monitor system sometimes measures energy in this way. In most cases, it is easy to monitor the coil voltage but rather difficult and/or expensive to monitor reliably the coil current.

A reasonable alternative is to monitor the coil voltage and the primary current to the isolation transformer. The secondary current waveform is virtually identical to the primary current but phase-shifted 180° (a very small amount of additional phase shift may be contributed by the output transformer magnetizing current). When the secondary current is used with an additional 180° phase shift at the feedback current transformer and corrected for the output transformer ratio, the result is a negligible difference in the measurement between a system using primary current or a system using secondary current feedback.

Coil voltages may be considerably different from job to job. Therefore, manufacturers will often standardize the design of energy monitor electronic circuits and feedback components for use on the primary of the output isolation transformer because the voltage range at that point is well known and remains the same from one application to another. It is also more economical with respect to feedback component cost.

One of the most common application problems with energy monitors and other monitoring systems is the attempt to set the limits too close to the established process value. The desired setup method for the energy monitor would be to develop a good part on the heat treating system and then run parts at 5% or 10% above and below this setting. The part should then be checked to see if it is in or out of spec. The desired upper and lower limits should be set just inside the limits that would cause the process to go out of specification. This will eliminate many problems of false tripping or rejection of good parts, but will prevent any bad parts from entering the production line. Customers who try to set the energy monitor or signature system set points to too tight a range may spend thousands of dollars on needless service calls.

7.13.6 Profile/Signature Process Monitoring

In the early 1980s, HWG-Inductoheat in Germany developed the coil signature system. The general idea of the signature concept is rather simple and can be described as follows. The monitoring system observes one of the unregulated variables related to the process and stores the most important parameters during the machine cycle. These values are compared to set points stored in the information bank within the PLC (ideal signature), and an output indication is given on the HMI readout. In normal performance, all subsequent signatures of cycles are compared to the ideal one and must remain between the upper and lower limits (Figure 7.65). If any signature goes outside the limit area, the operator can
see exactly during which part of the heat treatment cycle the signature was not repeated and the process exceeded the set limits. The operator knows immediately what the problem is and what should be done to adjust the machine to get the cycle signature back into the correct setup. It is not necessary for the operator to know in detail the electromagnetic, heat transfer, or quenching features of the process. He or she merely needs to know how to adjust the machine to get the signatures back to the ideal shape.

More modern monitoring systems have been developed using computer systems to give virtually unlimited storage capability to hard disks. The output provides a high and low set point display with the actual value being accumulated as the process is viewed. If any of the variables exceed the high or low set point, the system will give a warning of an unacceptable part. A variety of statistical process control (SPC) analyses can also be done on current data or data retrieved from past runs of a particular part.

A typical Inductoheat Induction Heat Treating Machine control for North America market in 2016 includes an Allen–Bradley Compact Logix PLC and Parker InteractX HMI (Windows-7 industrial PC) [665]. This system is responsible for all aspects of the machine operation, including workpiece processing and process quality validation.

Additional process quality validation can be performed by using existing sensors and PLC data and sharing them with an independent process validation system, which is often referred to as the “Profile & SPC Monitoring System.” The Profile/Signature and SPC application is intended for use in addition to the primary control system. The function of this system is to monitor and plot the analog signals of process parameters during the machine cycle (Process Profile or Signature) and to receive single data values for process parameters from the PLC at the end of the machine cycle to be used in SPC calculations. Data that fall outside specified ranges for either the Profile or SPC will cause the part(s) to be rejected. Data may be stored for future reference ranging from a period 1 month to indefinitely.

If any signature goes outside the limit area, the operator can see exactly during which part of the heat treatment cycle the signature was not repeated with specified accuracy. The operator knows immediately what the problem is and what should be done to adjust the machine to get the cycle signature back into the correct setup. The Signature monitoring system verifies all critical machine settings to provide confidence in the processing quality of the part.

Multiple process sensors wire to the PLC and are monitored during each machine cycle [665]. The information from these sensors is used to establish the “Accept” or “Reject” status.
of the workpiece. Typical items monitored include but are not limited to energy, water flow, water temperature, rotation speed and inverter volt–current–kilowatt meters, and so on.

The Accept or Reject decision is made in the PLC program at the end of the machine cycle based on whether the monitored parameters were maintained within low–high “Limit” values entered at the machine by setup personnel. Auxiliary contacts can be used to reject the part in automated lines or sound an alarm in manual operations.

The monitoring system can support single- or multistation operation. A liquid crystal display (LCD) or other type of graphics display is utilized to give a real-time signature or display of the magnitude of a specific variable with respect to time. Commonly, up to eight analog and eight SPC channels are supported for each station, giving a complete picture of what is happening during the cycle.

### 7.13.7 Protective Devices and Safety Principles

There are several variables that have more to do with operator safety and prevention of damage to the equipment than prevention of improperly heating the workpiece. These would include water pressure, water flow, ground fault detectors, safety interlocks, door switches, over-current protection devices, over-temperature protection, capacitor pressure, discharge circuits, and some others.

Operator safety is of paramount importance in the design of any industrial equipment. IH power supplies may operate with high voltages and currents and with components that can store and discharge energy. Safety interlocks are included on doors and guarding to ensure that the system power is removed if an operator enters an enclosure or guarded area. Output isolation transformers are often grounded on the secondary to prevent operator contact with DC voltage in the event of a transformer failure.

With respect to equipment protection, ground fault detectors are used to prevent damage to equipment if a moving workpiece touches the induction coil. Water flow and temperature protection are included to prevent failure of semiconductors, transformers, capacitors, and water-cooled current-carrying conductors. Over-current protection may be in the form of fast-acting semiconductor fuses or electronic limit or trip circuits. For the most part, this type of protection is set up to immediately turn off the HF output power and to remove all energy from the circuit. Latching control circuits are used with LEDs, LCD panels, or other types of displays to maintain a record of the circuit component causing the system to stop. Pressing a manual reset push button then resets the circuit.

### 7.13.8 Final Remarks

Different types of process monitoring systems are available on the market. The choice of a particular monitoring system is a matter of the operational features of the process, cycle time, technological requirements, and cost. In some applications, a relatively simple energy monitor will be sufficient. Other applications may require advanced signature monitoring devices.

Because of the production of modern HMI computer interfaces with much larger hard drive capacities, it is possible to integrate the machine control PLC, signature monitoring, and display functions with HMI along with the ability to include machine repair manuals and maintenance/set up videos to assist the operator and set up personnel in care and operation of the machine. The Inductoscan is an example of this type of modern modular system to address all of the customer’s needs in one package (Figure 4.66).
For the purist in machine control techniques, the obvious next step in the monitor and control area is to move from the point of observing that a part was not properly hardened to taking corrective action as the problem is encountered. For example, the use of a servo control valve would allow the control to raise or lower the quench flow or pressure when the value drops below the control set point. In this type of system, there typically would be two sets of set points around each signature: one pair of control set points and one pair of alarm set points. If the control set point were exceeded, corrective action would be taken. If the alarm set point were exceeded, the part would be classified as unacceptable.

Although technically feasible, this high-tech monitoring hardware may add considerable cost to the IH equipment while at the same time reducing the overall system reliability. Large amounts of data may be gathered, which must then be analyzed in order to assess the effect that a change in each may have on the process. All of this takes time and costs money. In many instances, the more prudent approach may be to utilize some of the basic monitoring and control techniques mentioned above, with general preventive maintenance and common sense to maintain consistently reliable results. For the prudent engineer, the question changes from “What can be done?” to “What needs to be done?”
Epilogue

Dear Reader,

You have now completed the last page of the second edition of our *Handbook of Induction Heating*, and we hope that the material presented will be useful to you. Based on the experience of our colleagues around the world and our own knowledge, we have tried to provide you with state-of-the-art materials devoted to modern induction heating, heat treating, joining, coating, and other applications utilizing electromagnetic induction, as well as aspects related to metallurgy, materials science, equipment design, process monitoring, diagnostics, quality assurance, controls, modern semiconductor power sources, etc. Due to space limitations, we discussed only specially selected aspects of modern electromagnetic induction.

When we started to write the second edition, we had originally planned to discuss a much larger variety of applications, processes, and phenomena. Our intention was to combine a discussion of achievements accumulated at Inductoheat Inc. with technology provided by other companies in the Inductotherm Group, which comprises more than 40 companies strategically located around the globe.

Each company of the Inductotherm Group excels in certain areas of electromagnetic thermal processing, where it holds a world-leading position. Many of those companies you probably already know by their individual brand names including Inductoheat, Inductotherm, ThermaTool, Consarc, Radyne, Banyard, Alpha, and many others. As a multitechnology organization, the Inductotherm Group offers many advantages including being able to handle a customer program of any size as a single-source supplier, while providing aftersales support through a global network of manufacturing and service facilities. Inductotherm Group engineers and scientists throughout the world communicate daily to exchange ideas. This saves customers time and money because many new applications can be efficiently handled by modifying proven designs that already exist at one or more of the companies.

Today, all Inductotherm Group companies employ advanced computer-aided techniques to simulate, design, and test machines. Production-scale process development machines are maintained at most plant locations. New applications are proven by running customer parts or prototype work under production conditions.

Superior technology, application experience, and scientific and engineering depth are only part of the Inductotherm Group story. Equally important is the aftersales support, which includes operator training, maintenance training, and educational seminars around the world. These seminars allow present and potential users of induction technologies to understand basic and advanced knowledge associated with electromagnetic induction and to be on top of novel theoretical achievements and process developments.

Once again, due to space limitations, we concentrated materials presented in the second edition on the most common physical phenomena and processes. We have tried to provide the industry and academia with a helpful engineering guide to modern induction heating and heat treating. We systematized existing and new information, described advanced computational techniques, clarified common misconceptions and confusions existing in different publications related to electromagnetic induction, and provided practical recommendations and the latest theoretical and practical achievements.
Some people traditionally view an induction heating as a “standalone” process or system. In materials presented, we have tried to introduce the advanced design philosophy that requires the process to be considered part of an integrated system that includes all elements (such as previous process stages and metallurgical subtleties, stress analysis, part handling, load matching capabilities, and many others) that must be considered in order to accomplish the process goal.

Hopefully, some of our readers will provide new ideas to improve the materials presented here. We would appreciate any comments and suggestions you may have. Your recommendations on improving the materials presented here are very important to us.

Finally, we would like to invoke a popular saying of Mr. Henry Rowan (the founder of the Inductotherm Group companies): “This country doesn’t just need more engineers, we need more great engineers.” We feel that this saying can well apply not only to a particular country but to the world as well. Because you decided to read this material, it means you are looking for something new, something superior to what you already have or already know. It means that you want to be a part of the society of great engineers and successful professionals. We hope that the material presented here will help you to better understand the intricacies of thermal processing using electromagnetic induction, and become a “world-class” user of this remarkable technology. If you have questions or suggestions or would like to acquire more information, we welcome you to contact us at Inductoheat Inc. in Madison Heights, Michigan, USA or visit http://www.inductoheat.com or http://www.inductothermgroup.com.

Sincerely yours,

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