



FLUXTROL®

ASM Handbook Volume 4C
Induction Heating and Heat Treatment

Article:

— Design and Fabrication of Inductors for Induction Heat Treating —



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About Fluxtrol

Magnetic Flux Controllers made of Fluxtrol® and Ferrotron® soft magnetic composite materials (SMCs), are powerful tools in induction heating coil technology. Typically, the main reason for using our magnetic field concentrator in induction heating systems is to amplify or reduce the magnetic field in a specific area. Soft Magnetic Composites (SMCs) manufactured by Fluxtrol, Inc., under the brand names Fluxtrol®, Ferrotron®, and Alpha-form® are primarily used to enhance magnetic fields. Applying our SMC products to your induction coils is the most effective way to improve its performance, control heat patterns, and achieve energy savings. Their realized benefits of using our products include:

- Improvement of the induction coil and process efficiency
- Improvement in coil power factor
- Reduction in coil electrical current
- Reduction of unintended heating of machine components
- Reduction in undesired heating of areas of the workpiece
- Precise control of the magnetic field and resulting heat patterns
- Improvement in the efficiency of the high-frequency power supplying circuitry
- Reduction of external magnetic fields in close proximity to the induction coil

In most applications, multiple benefits usually occur. These SMCs serve different functions in induction heating installations.

Soft Magnetic Composite (SMC) materials produced by Fluxtrol, Inc. are advanced engineered materials composed of a soft-magnetic component (usually iron and iron-based alloy powder metal) and a dielectric component (generally an organic polymer binder). The soft magnetic part offers a good path for the magnetic field to pass through. The dielectric part electrically isolates magnetic particles from each other, which helps reduce eddy current losses.

Fluxtrol produces two main types of soft magnetic materials: machinable and formable. Our machinable materials, Fluxtrol® and Ferrotron®, are typically made through powder metallurgy compaction, followed by heat treatment to improve their magnetic and mechanical properties. Machining Fluxtrol SMC materials is

easier than machining SiFe laminations. They are applied to induction coils using an adhesive and mechanical supports. Fluxtrol formable SMC Alpha-form® is molded around the surface of the induction coil, secured mechanically, and cured in an oven to set its shape.

Over time, Fluxtrol has helped educate customers on the role of magnetic flux controllers in induction heating systems through comprehensive studies involving computer simulations and experiments, and has brought new ideas to the table on how to best utilize these unique materials and support their expansion into new areas. Today, these SMCs serve many different functions in induction heating, cold crucible melting, inductively coupled plasma, and induction welding installations, to name a few. In addition to thermal processing technologies, Fluxtrol SMCs have been applied in multiple high-tech electromagnetic devices and sensors. Depending on the application, our SMCs are referred to as magnetic field concentrators, magnetic flux controllers, diverters, field intensifiers, magnetic cores, impeder cores, yokes, shunts, and screens.

Fluxtrol is not just a materials supplier; we are a technology partner. We not only develop the materials that improve your system's performance, but also work collaboratively with our customers to develop the best system together. We are frequently asked to work as part of our partner's development team, providing our complementary skills in magnetic flux control and materials processing with their core competencies. Together, this helps to make the best solutions that lead to next-generation materials and world-class production capabilities, giving our partners a competitive advantage. Some of our relationships are on a contract basis, but others are much more holistic, such as supporting student research, serving as an industrial advisor for young researchers, participating in conferences/seminars, or publishing white papers. We truly believe that the more people understand induction technology, the more it will help the field grow and support the continued expansion of our magnetic flux control-based induction technology business. This article, reproduced with permission from ASM Handbook, Volume 4C: Induction Heating and Heat Treatment, demonstrates Fluxtrol's commitment to sharing information about this important technology.

Design and Fabrication of Inductors for Induction Heat Treating

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FOR INDUCTION MELTING AND MASS HEATING, the early induction heating coils were manufactured from copper tubing wrapped in multiple turns around a mandrel. The first induction heat treating coils were developed for crankshaft hardening in the 1930s (Fig. 1, 2) (Ref 1–4). Unlike the melting and mass heating coils, the heat treating induction coils were machined. These inductors consisted of two parts with a hinge on one side that would open and shut around the crankshaft journal. Quench holes were drilled on the inner diameter of the induction coil to deliver quench to the part after heating. This pioneering development was the culmination of many years of hard work by a large team and clearly demonstrated the different requirements for induction heat treating as compared to melting and mass heating.

During the infancy of induction heat treating coil development, the specific features of the induction coil primarily were determined through an analytical-, experience-, and experimental-

based method. Concepts for induction coils were created by physicists. Calculations of coil parameters were determined by manually solving complex equations. Induction coil designs initially were made by draftsmen on blueprints. Most inductors were manufactured by craftsmen using a combination of copper tubing, manually machined components, and copper plates brazed together. Coil optimization was made based on experimental results through the trial-and-error method, because tests and modifications took much less time than the calculations did (Ref 1, 5).

While many induction heat treating coils are still manufactured in this way, the tools for the design and fabrication of complex induction heat treating inductors have evolved greatly over the years. For many types of applications, the preferred induction coil style already is known based on years of empirical data. In many cases, comparisons to known results can even determine induction coil dimensions that will lead to a successful heat treating pattern, greatly limiting experimental testing times and shortening development cycles (Ref 1, 5–9).

For newer applications or optimization of existing ones, computer modeling tools are being incorporated into the induction coil design procedure. Sophisticated software running on

personal computers is capable of making calculations in seconds, minutes, or hours that would have taken days, weeks, or months to solve manually. In many cases, no analytical formula exists for complex coils, and the only way to make calculations prior to tests is with a computer modeling program. Induction coil designs and process recipes are “virtually” tested to determine resulting heat patterns. In many cases today (2013), virtual tests and evaluations can be made more quickly and at a lower cost than physical ones (Ref 10–12).

The process of mechanical induction coil design also has evolved over the years. While the initial drawings were made by hand, induction coils now are drawn and detailed using computer-aided design (CAD) packages. Over the past several years, CAD packages have increased their interactivity with computer-aided manufacturing (CAM) software packages. In many instances, induction coil drawings can be transferred from a CAD drawing to a CAM program into the computer numerically controlled machine. This creates the possibility for greater repeatability of complex machined induction coils (Ref 13, 14).

Methods of Induction Heat Treating

Today (2014), there are many different types of induction heat treating coils. The induction heat treating coil style depends on the induction heat treating process. All induction heat treating processes can be classified in two categories: single shot and scanning, based on whether the induction coil is moving (excluding rotation) relative to the part during the heating process. A brief description is given subsequently, because more in-depth information on induction heat treating equipment is discussed in other sections in this article.

In single-shot (Fig. 3) induction heat treating applications, the position of the induction coil relative to the heated length of the part does not move. In many single-shot heating

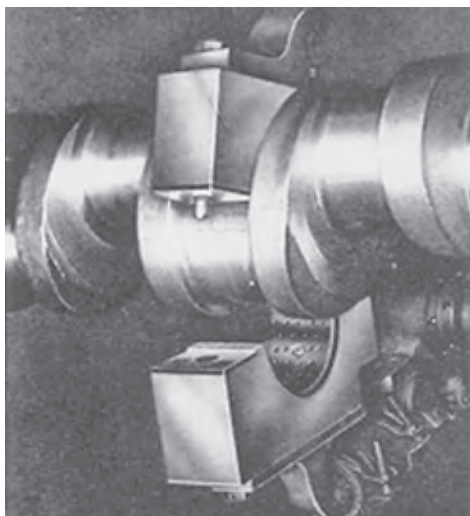


Fig. 1 Tocco coil. Source: Ref 1

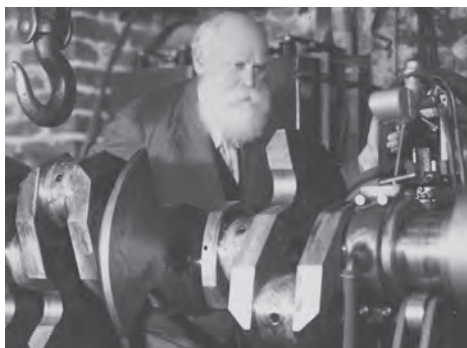


Fig. 2 Vologdin coil

applications, the part rotates while heating and quenching occur to ensure uniformity of pattern. Within the family of single-shot heat treating applications, there are several varieties of induction coil configurations, depending on the quench-delivery mechanism.

Machined integral quench (MIQ) installations have quench integrated right into the induction coil itself. The most common method is for the quench to be delivered through the coil copper itself. These inductors typically have separate pockets for water cooling and quench delivery. In some other cases, the quench may be delivered through a magnetic flux concentrator.

Another type of single-shot heat treating installation is quenching in place (Fig. 4). Quenching in place is similar to MIQ, because the quench ring is a part of the induction coil assembly. What differentiates quenching in place from MIQ installations is that the quench is not designed to be an active component of the induction circuit.

The final single-shot induction heat treating coil style is separate quenching (Fig. 5). In these installations, the quench is not part of the induction coil assembly. In separate-quench installations, the quenching often is delivered in a different station or position in the machine. These systems are common when a delay between heating and quenching for heat soaking is desirable.

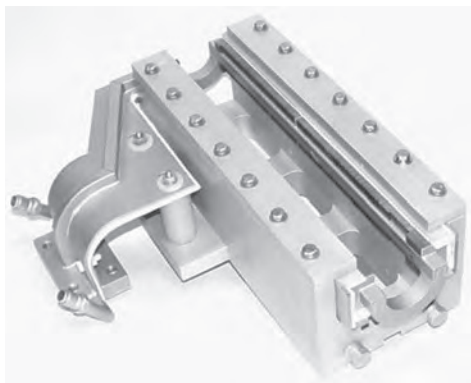


Fig. 3 Single-shot induction heat treating application

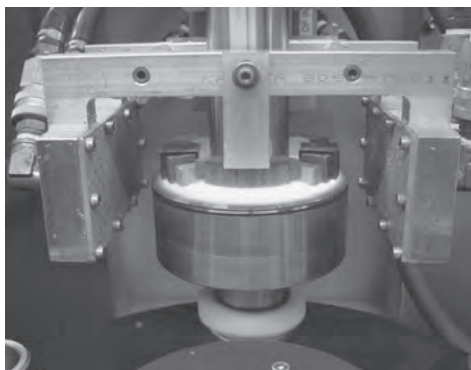


Fig. 4 Quench-in-place inductor for hardening of a spindle

Besides single shot, the other type of induction machine is scanning (Fig. 6) (Ref 5, 9). In scan-hardening applications, the induction coil moves relative to the part. Similar to single-shot inductors, scanning inductors can be either MIQ or quenching in place. They also may be separate quenching, but this is less common.

Considerations for Inductor Design

Induction heat treating coils are available in many shapes and sizes and must perform a variety of tasks in a given induction heat treating application. Depending on the application, the induction coil design requirements include:

- Meet heat treatment specifications in desired production rates
- Be robust enough to tolerate manufacturing variations
- Mount into the induction machine
- Have electrical parameters that match the induction power supply
- Deliver quench
- Have a satisfactory lifetime
- Have satisfactory efficiency
- Be repeatable from inductor to inductor

In developing a new induction heat treating coil and process, the first question is whether

the component will be produced on an existing system or if a new machine must be built. In many cases, the part producer's desire is to develop new tooling for an existing machine with spare capacity. This reduces the degree of freedom and can make the induction coil design procedure more complicated, because a less-than-optimal frequency or coil style will be necessitated to fit the existing machine (Ref 16).

To determine the ability to use existing equipment, it is necessary to make an analysis of the part to be heat treated. Part material, prior processing, geometry, production rate, and heat treatment specifications all play roles. The part material and prior processing determine what the minimum heat treatment temperature should be, along with how much time is allowed for cooling. The part geometry and heat treatment specifications indicate how much energy is required, what the preferred frequency ranges are, and what type of induction method (i.e., single shot, scanning) is best suited for the application. Finally, the production rate determines how much power and/or how many spindles or stations are required.

More details on this topic are given later in this and other articles in this Volume. The discussion in this article is limited to the relationship between these factors and the induction coil design.

Current Flow in the Part

Eddy currents are the primary source of power dissipation in most induction heat treating applications. Eddy currents, just like all other electrical currents, must form a closed contour. In most cases, the current flow in the workpiece follows the shape of the induction heating coil, due to the proximity effect. The power density in a given section of the workpiece depends on the current density. The current density can be influenced by electromagnetic effects (end effect, edge effect, etc.), the presence of magnetic flux concentrators, the width of the copper, the geometry of the part, and the distance between the coil and the workpiece (coupling gap).

The next step in the coil design process is determining how the current will flow in the part. This is critical, especially in cases where the geometry changes. Some common geometry changes encountered in induction heat treating are fillets, undercuts, corners, shoulders, chamfers, splines, keyways, and oil holes. The heating of these critical areas relative to adjacent ones is strongly dependent on the induction coil style and frequency of heating.

The first primary choices for current flow, either in the plane of the geometry change or perpendicular to the geometry change, are discussed here. When current flow is perpendicular to the direction of a geometry change, the natural tendency is for the current to concentrate on the part surface that is closer to the



Fig. 5 Separate quenching. Source: Ref 15

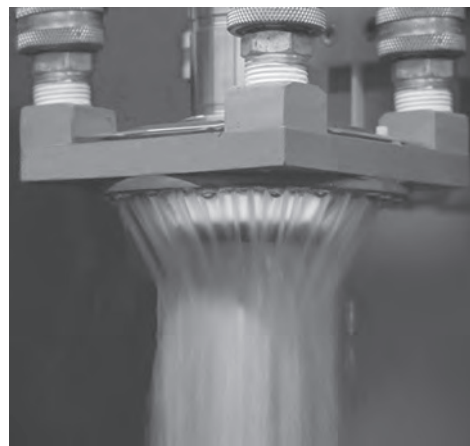


Fig. 6 Machined integral quench scanning inductor with magnetic flux concentrator

induction coil, due to the proximity effect. An additional consideration is that near the ends of the closer section to where the distance increases, there is either a decrease or an increase in heating, depending on whether the part is magnetic or nonmagnetic due to the electromagnetic end effect. For hardening applications, there is some increase, and for tempering there is a decrease. The magnitude of the change depends on the frequency (Fig. 7) (Ref 12).

When the current flow is in the direction of a geometry change, the current flows under the inductor in a width approximating that of the induction coil. When the dimension change occurs, the current flow follows the contour of the part through this dimensional change. At the point of the dimension change, the change in heating is governed by the electromagnetic edge effect. The edge effect tends to be smaller than the end effect, hence meaning a smaller temperature differential in this area. As the distance between the coil and part increases, the amount of current remains nearly the same,

but the current begins to flow over a wider length. The less concentrated heating leads to lower power densities (Fig. 8). The difference between the power densities tends to be smaller than when current flow is in the direction of the geometry change than when it is perpendicular.

To illustrate the concept, consider the case of a simple spindle with one bearing race and a shoulder (Fig. 9). The heat treating pattern is the light-gray area. This part could be heated either by scanning or single shot. The scanning inductor almost certainly would be an encircling inductor with a length less than the pattern length. Within single shot, it also could be hardened by a machined encircling inductor or a so-called encircling/nonencircling inductor.

For an encircling inductor (scanning or single shot), the current flow in the coil and part tend to take the shortest path and flow along the inductor inside diameter and bearing surface diameter. To compensate for this tendency, it is necessary to vary the gap between the coil and part to use the proximity effect to

compensate for the shorter length for current flow. In the area of the radius, there is a transition from the smaller gaps on the flange to the larger gaps on the diameter. For a single-turn machined inductor, the coil design in this area involves a delicate balance to achieve sufficient depth in the fillet without heating too deeply in the bearing area just above the fillet. For case depths that are large relative to the cross section, this becomes more difficult because core temperatures increase, resulting in reduced conductive heat extraction. For a shorter scanning coil, this task is made easier by using a magnetic flux concentrator to drive current down from the shaft and into the radius of the part (Fig. 10).

Encircling/nonencircling inductors consist of multiple partial loops connected by copper rails that are contoured to the part surface (Fig. 11). For these inductors, the part must rotate to ensure even heating. For a simple part such as this, likely only one top and one bottom partial loop would be required. In this case, current flows under the coil turns and follows the contour of the coil in the part. In this way, the top and bottom of the pattern are controlled by the end loops, and the rails determine the pattern in the central area. By following the rails along the part surface, the current flows through the radius.

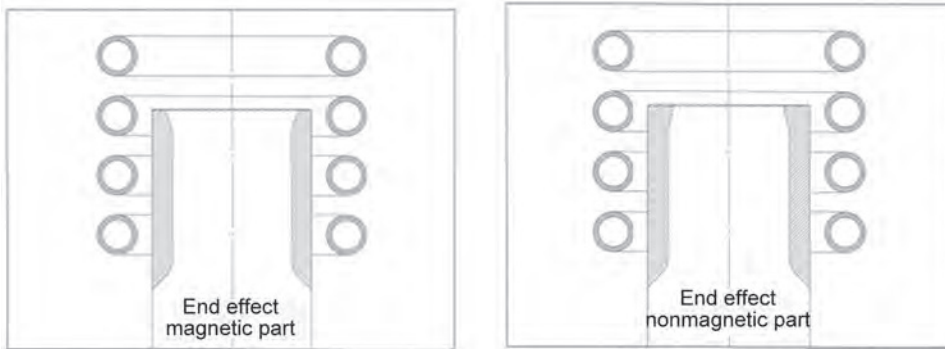


Fig. 7 End-effect drawing

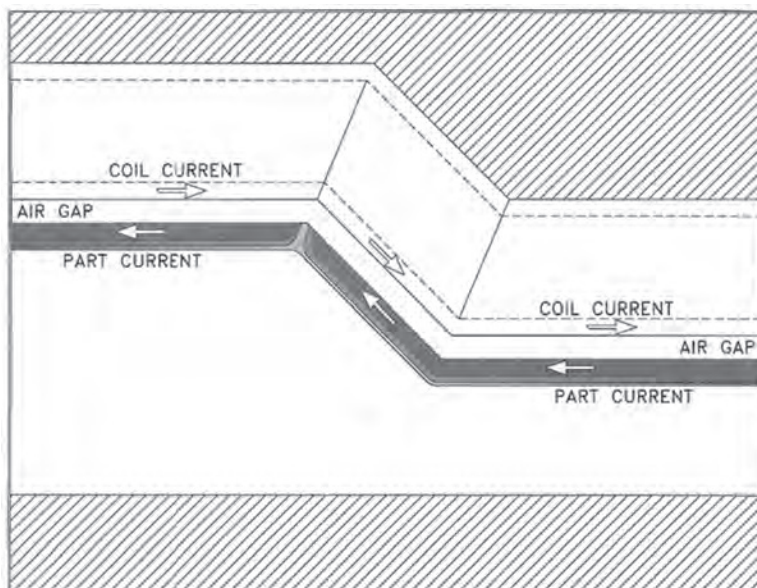


Fig. 8 Edge-effect drawing

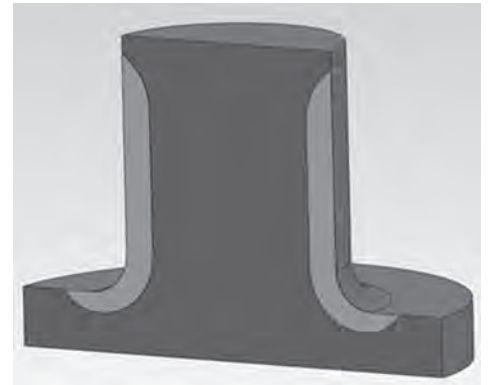


Fig. 9 Heat pattern for spindle

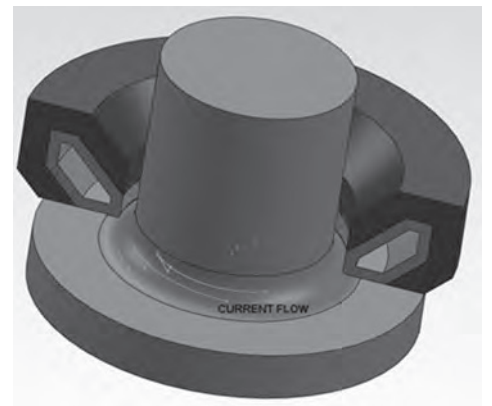


Fig. 10 Encircling drawing for spindle

This makes achieving a more uniform contour easier with a linear inductor than with an encircling one for this type of part (Fig. 12).

The Influence of Frequency

The frequency of the induction heating current has a strong influence on the induction coil and process design. It affects the power required, heating time, coil losses, local distribution of power in the part, and the structural support required. A brief overview of the effect of frequency is given in this section, because it is covered in more depth in other articles in this Volume.

Often, the same case depth can be achieved over a wide range of frequencies. For large parts in either the completely magnetic (cold steel) or nonmagnetic (hot steel) state, current density is highest at the surface and falls off

exponentially in depth. There is a value used by induction heating practitioners called the reference or skin depth related to this behavior. The formula for reference depth is:

δ = k√(ρ/μf) (Eq 1)

where δ is the reference depth, k is a constant depending on units, ρ is the electrical resistivity, μ is the magnetic permeability, and f is frequency.

In large bodies, 63% of the current and 86% of the power reside in the first reference depth (Fig. 13) (Ref 6, 17). This leads to the assumption commonly made in estimating parameters that all of the power is generated in the δ layer.

In induction hardening applications, the distribution of current and power density is different than that predicted by the reference depth, because the magnetic steel below the

Curie point still interacts with the magnetic field behind the nonmagnetic hot surface layer (Ref 17). To achieve the same case depth on parts with lower frequencies, one can expect higher power levels, shorter heating times, and lower surface temperatures. As the frequency is increased, power levels must be decreased and heating times increased to achieve the same case depth without overheating the surface. The amount of energy required depends on the balance between thermal losses (heat soaking), coil efficiency, and power induced in the subcase-depth material.

Besides the process, the frequency also influences how the current is flowing in the induction coil itself. In practice, the most effective thickness of the conductive part of the tubing wall (d1) is assumed to be d1 ≈ 1.6δ1. This ratio is based on solution of a one-dimensional problem. An induction coil tubing wall smaller than 1.6δ1 results in reduction in coil efficiency; furthermore, in some cases the tubing wall can be much thicker compared to the aforementioned ratio. This is because it may not be mechanically practical to use a tubing wall thickness of 0.25 mm (0.01 in.). Some guidelines for wall thickness are shown in Table 1 (Ref 9).

The frequency also affects the electrodynamic forces, which influence the mechanical design of the induction coil. Electrodynami c forces in induction heating have two components: static and dynamic. The static component initially pulls the inductor in toward the part in the cold magnetic state and then pushes it away from the part when it is nonmagnetic. The dynamic component oscillates around the static component at double the electric frequency (Fig. 14). The level of force in the system is proportional to the square of the coil current; that is, the forces are directly proportional to the power (Ref 17).

When the part is electrically thick (i.e., the diameter or thickness is much greater than the reference depth), the current required for the same power is proportional to the inverse fourth root of the ratio of frequencies (Eq 2). From this equation, it can be seen that the current required for the same amount of power decreases with increasing frequency:

I2 = I1√(f1/f2) (Eq 2)

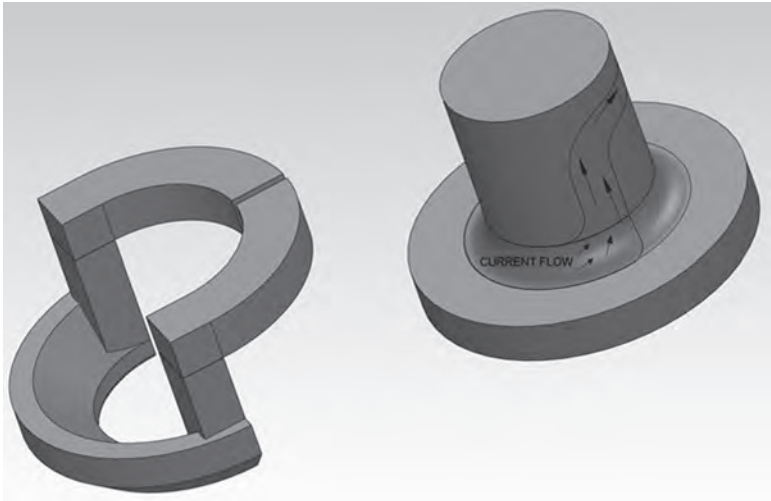


Fig. 11 Encircling/nonencircling drawing for spindle

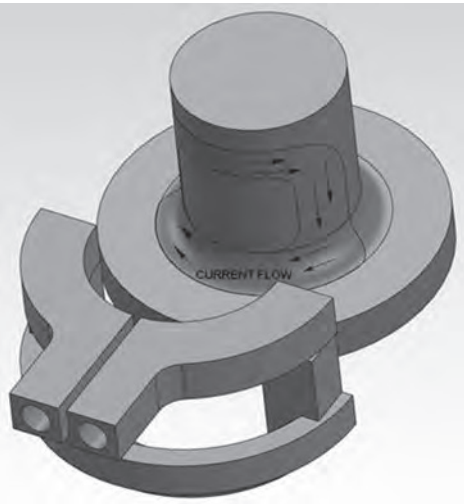


Fig. 12 Linear/single-shot drawing for spindle

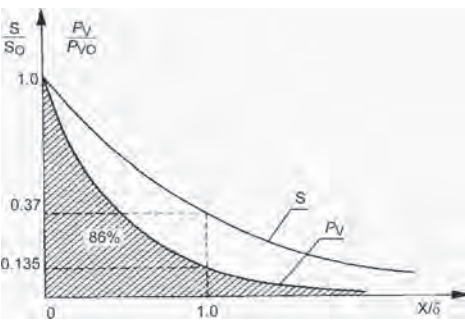


Fig. 13 Distribution of current (S) and power density (Pv) in the depth of a large workpiece. Source: Ref 17

Table 1 Standard wall thickness of copper tubing

Copper wall thickness		Frequency, kHz
mm	in.	
0.75–1	0.032–0.048	450–50
1–2	0.048–0.090	25–8.3
1.5–4	0.062–0.156	10–3
4–6.5	0.156–0.250	3–1

Source: Ref 7

Due to this, the electrodynamic forces are higher at lower frequencies. Additionally, power levels generally tend to be higher at lower frequencies, increasing the electrodynamic forces even more. Therefore, the lower the frequency, the more robust the mechanical design of the induction coil should be. In addition to heavier copper wall thicknesses, the coil supporting structure also must be stronger to withstand the mechanical loading to which the coil is exposed. This is especially true on single-shot coils.

Control of Heating in Different Areas of the Part

In many induction heat treating applications, there is a requirement to selectively harden some areas of the workpiece and not harden others. In other instances, different case depths are desired in different areas of the part. Often, it is necessary to achieve these various targets in the same induction heat treating operation.

For scan hardening applications, these variations typically are compensated for by adjusting the power and scan speed as the part traverses through the induction coil. For single-shot induction coils, it is necessary to accommodate these changes in the coil design. There are three main tools for adjustment of the coil design: coupling gap, coil copper profile, and magnetic flux controllers.

The coupling gap is the most straightforward way to control the heat pattern. The closer the coil is to the part, the greater the intensity of heating in this area relative to other areas. This is because the current in the part flows in a narrower band more closely approximating that in the induction heating coil. With increasing coupling gap, the current spreads out over a longer length, resulting in lower current density and power density.

Another method to control the heat pattern is to change the cross-sectional profile of the copper coil. The section(s) of the coil turn that faces the part and carries the majority of the

current is referred to as the heat face of the coil. For induction coils with a single heat face, power profiling is achieved by varying the geometry of the heat face (Fig. 15). For instance, to shorten the transition zones at the ends of the coil, it is common to have a larger gap in the middle of the coil than on the ends. This method is commonly used for controlling the end of a heat treating pattern where it is desirable to keep the pattern out of an undercut or a snap ring groove. This helps to compensate for the divergence of magnetic flux and the additional thermal losses near the end of the coil.

An example of this is hardening the bearing of a crankshaft using an encircling coil (clam-shell or sharp-C technology, Ref 9). Using the Flux 2D computer simulation program, it is possible to make a comparison to see the effect of the copper profiling on the temperature distribution. Figure 16 shows a simplified example of a coil for this technology. The lines on the part represent the minimum and maximum case depth. The frequency for this comparison is 50 kHz. The coupling gap is 2 mm (0.08 in.), and the coil has thin plates of Fluxtrol 50 concentrator on both sides to prevent coupling with the sidewalls. At 2.5 mm (0.10 in.) from each end of the coil, the copper is recessed 1 mm (0.04 in.). This coil is compared to a coil with

the exact same geometry, except the central section of the inductor is not recessed. The heating time for both cases is 4 s.

The temperature distribution in the coil without profiling is shown in Fig. 17. The area of high temperature begins to taper off well before the end of the heat face and the minimum required length of the pattern. The surface temperature already is high, so it is not possible to increase heating to lengthen the pattern.

Figure 18 shows the temperature distribution for the coil with a profiled face. It is clear from this image that the area of high temperature extends significantly longer than for the coil without profiling. The minimum heat treatment width is met with a lower maximum surface temperature. For better comparison between the two cases, Fig. 19 compares the surface temperature in length.

For coils with multiple heat faces or sections, in addition to the coupling gap, the heat pattern also can be controlled by changing the width of the heat face from section to section. Power density in the part is proportional to the current density squared. If it is assumed that all of the current in the coil is transferred to the part and is flowing directly under the heat face of the induction coil, then the current density will be inversely proportional to the width of the heat face. This means

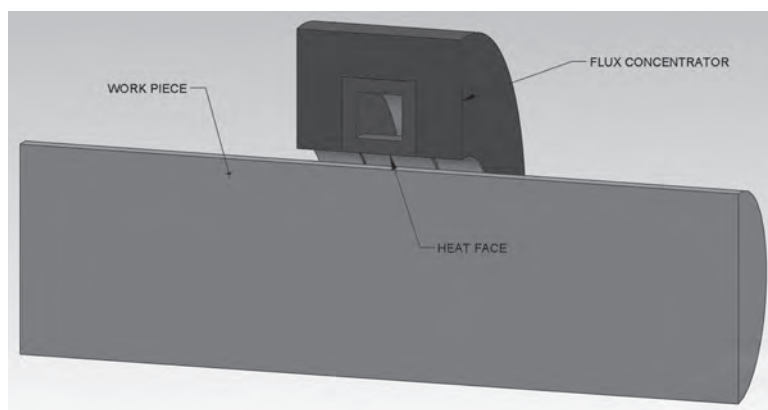


Fig. 15 Drawing showing inductor heat face

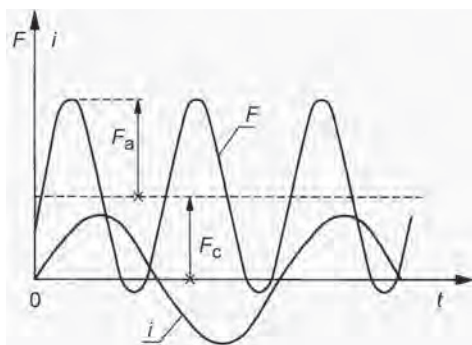


Fig. 14 Diagram showing relationship between current (i), static component of force (F_c), and dynamic force (F). Source: Ref 17



Fig. 16 Nonrotational inductor cross section used for simulation

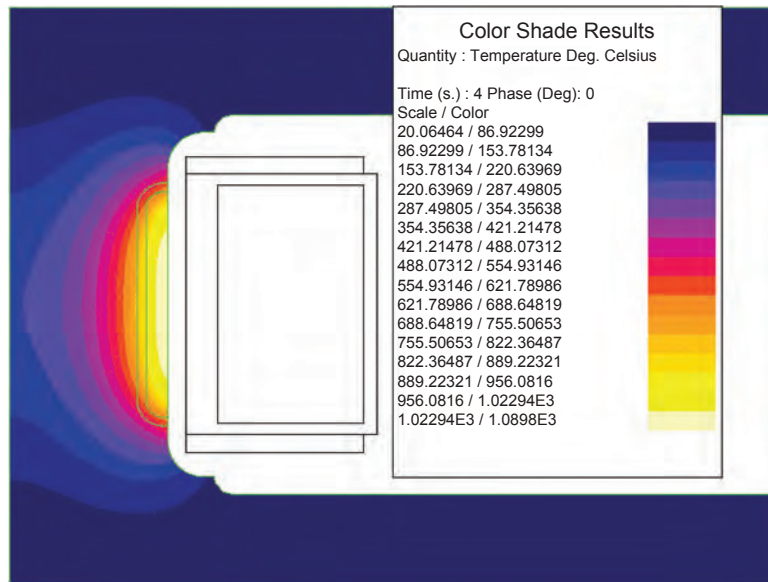


Fig. 17 Temperature distribution with a nonprofiled heat face

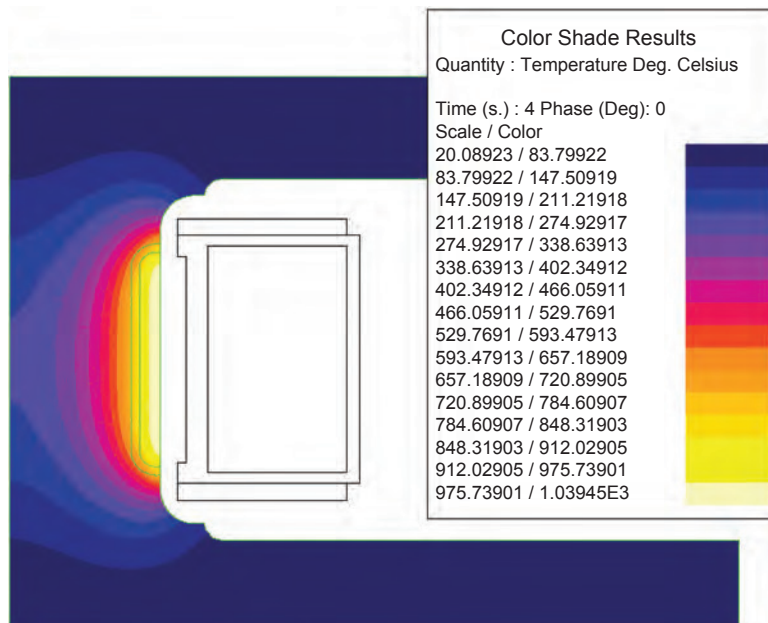


Fig. 18 Temperature distribution with a profiled heat face

that power density will be proportional to the inverse square of the width of the heat face. The real effect is significantly less, because not all of the current is on the heat face, and some of the flux outside the coil couples with the part.

For heating of a round part with a linear coil, the effect is not as strong due to the nonuniform gap between the rectangular coil and the round part.

To demonstrate the effect of the heat face width, a comparison is made for heating a

12.7 mm (0.5 in.) thick plate with a 9.5 by 12.7 mm ($\frac{3}{8}$ by 0.5 in.) tube and a 12.7 mm (0.5 in.) square copper tube. Computer simulation program Flux 2D is used for calculation of the electromagnetic problem. The top half of the plate has the properties of steel above the Curie point, and the bottom half has the properties of cold steel. The frequency is 10 kHz, and the coupling gap is set to 3.2 mm ($\frac{1}{8}$ in.). The same current, 3000 A, is used for both coils. The magnetic field and power density distributions for both cases are shown in

Fig. 20. Ideally, the power density would be 78% higher for the 9.5 mm ($\frac{3}{8}$ in.) heat face compared to the 12.7 mm (0.5 in.) one. In reality, this difference in maximum power density is only approximately 17%. This is due to the large amount of current that is flowing in the part outside the heat face of the coil.

A more effective way to control the distribution of heat in the length of an inductor is to use magnetic flux controllers. For induction heat treating applications, the most common materials used as magnetic flux controllers are silicon steel laminations and soft magnetic composite materials. Magnetic flux concentrators provide a low reluctance path for the magnetic field to flow. The result is that the magnetic field goes from being widely distributed in space to being concentrated around the coil. This causes nearly all of the current flowing on the sidewalls of the copper coil to be pushed down to the heat face. This results in the current in the part being concentrated more strongly underneath the heat face of the coil.

To demonstrate the effect of the concentrator, a comparison is made for heating a 12.7 mm (0.5 in.) thick plate with a 12.7 mm (0.5 in.) square copper tube, with and without a C-shaped concentrator applied. The flux-concentrating material used is Fluxtrol A. The other conditions are the same as in the case for the heat face variation study. The magnetic field and power density distributions for the coil with concentrator are shown in Fig. 21.

The magnetic field and power density are much more concentrated when the magnetic flux controller is applied. The surface power density curves from the left to the right side of the part are shown in Fig. 22 for all three cases. It is clear that the application of a magnetic flux controller is a stronger method of controlling the heat pattern in the length of a coil than the use of copper profiling. It also is possible to more smoothly distribute the pattern between different areas by profiling the poles of the concentrator rather than having steps in the induction coil. For linear coils heating a round part, the influence of both heat face width and a magnetic flux controller is less dramatic than in the case of a flat plate, due to the divergence of the part from the coil. More information on magnetic flux controller selection and uses is contained in the article "Magnetic Flux Controllers in Induction Heating and Melting" in this Volume.

Presentation of the Part to the Inductor

During the initial inductor design, a method of holding the part and presenting it to the inductor must be addressed. Some considerations are:

- What is the part size and weight?
- What is the process hardening or tempering?
- Is it to be scanned or single shot?

- Is the part to be rotated during processing?
- What is the rate of production?
- What type of materials handling equipment is needed?
- How and where on the part can it be held?
- What is the kilowatt requirement and power supply frequency?
- How is it to be loaded into the inductor: manually or mechanically?
- What is the quench method: spray, dunk, agitated bath, still air, or air blast?
- What types of holding devices are to be used: centers, chuck, or special grippers?

Depending on the process, there could be several mechanical methods to grip and present a part to the inductor. In high-production applications, an entire machine may be designed and built for a specific materials handling process. In limited-production runs, however, a simple lift-and-rotate device within a quench tank may be employed. Either way, a decision must be made on how to hold the part.

Part holding and presentation can be as easy as chucking the part or as complicated as having to hold and rotate the part while it is heated entirely. In any scenario, the electromagnetic

fields from the induction coil should be considered in the design of the holding device and its effect on the part. Magnetic steels in close proximity to the inductor will heat; therefore, sufficient air space around the inductor is prudent. Common nonmagnetic part-holding materials, such as 300-series stainless steels, aluminum, and brass, can be heated when in close proximity to the inductor, but with a less significant effect. When designed specific to an application, certain ceramics also make excellent part-holding devices.

For example, typical to induction hardening applications is the lift-and-rotate method within a quench tank. A part of reasonable size and shape, such as an automotive wheel spindle, is mounted onto a part holder made from nonmagnetic stainless steel. An upper center of the same material is used to stabilize the part during rotation. An inductor designed to heat treat the wheel spindle is installed onto the power supply mounting foot within the tank. A spray quench is integral to the inductor. The wheel spindle is loaded in the holder and raised to the inductor. Rotation starts, the induction power is applied, the wheel spindle is heated and then immediately quenched, and the spindle is lowered and unloaded. This entire process takes less than 30 s. In a high-production application, throughput would be multiplied with additional heating stations employing various materials handling systems.

While many examples of heat treating are typical, when parts are large and/or geometrically difficult, the presentation to the inductor may require engineering. For many induction-hardened parts, rotation during heating equalizes the heat treating pattern. Some parts, such as truck steering arms in the shape of the letter “J,” cannot be rotated 360° due to the J-hook

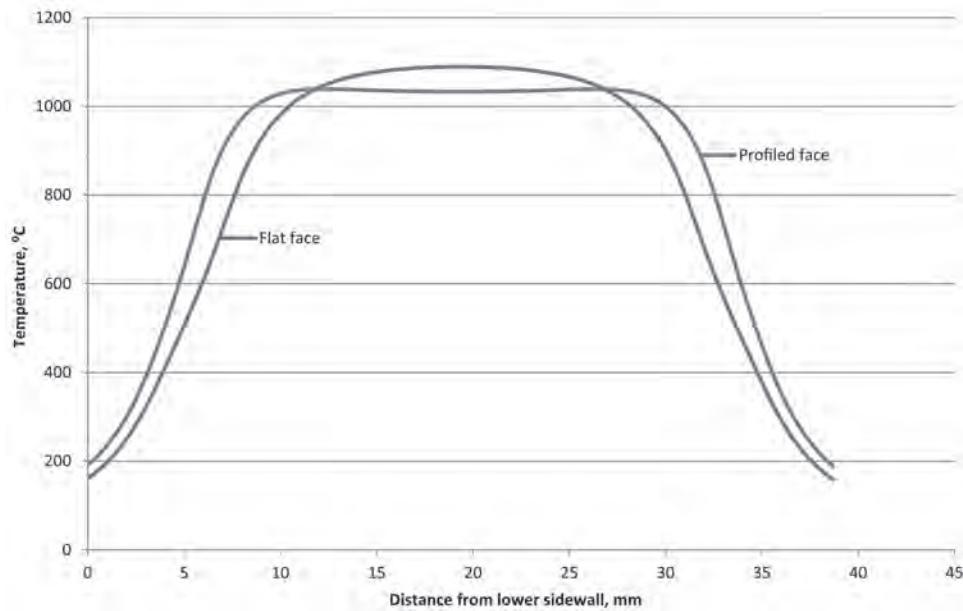


Fig. 19 Comparison of temperature distributions with and without profiling for nonrotational heating of a crankshaft

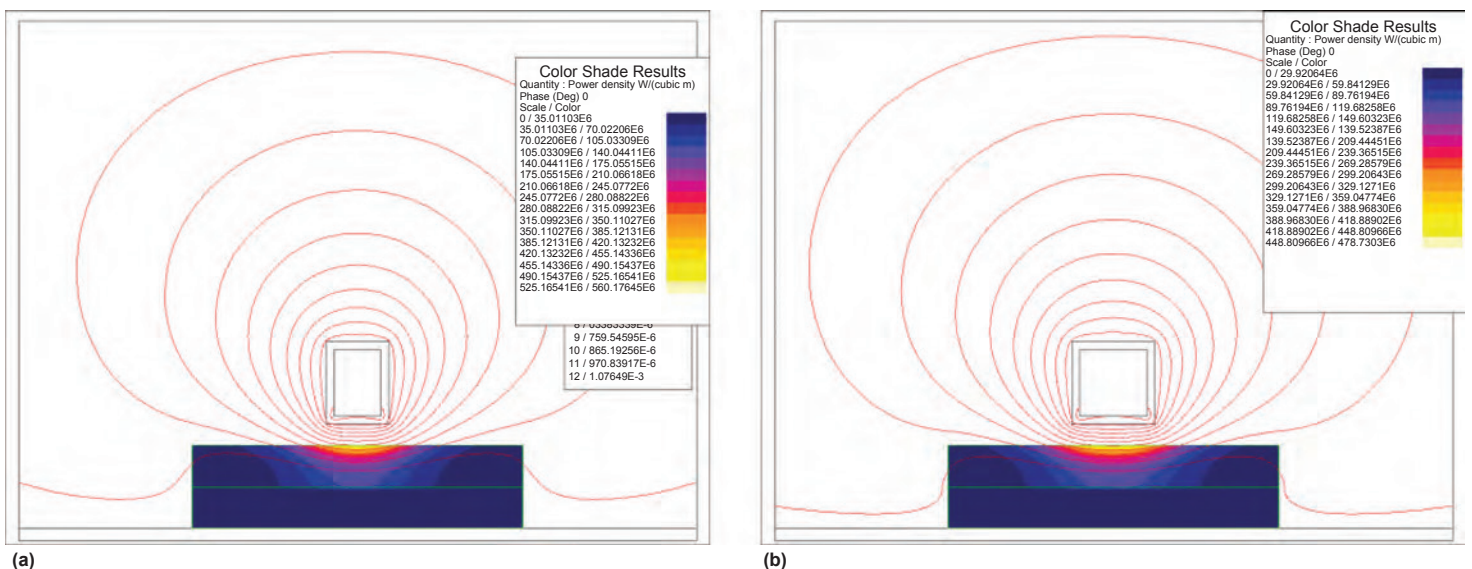


Fig. 20 Comparison of (a) 9.5 mm (3/8 in.) and (b) 12.7 mm (0.5 in.) heat faces for heating of a flat plate

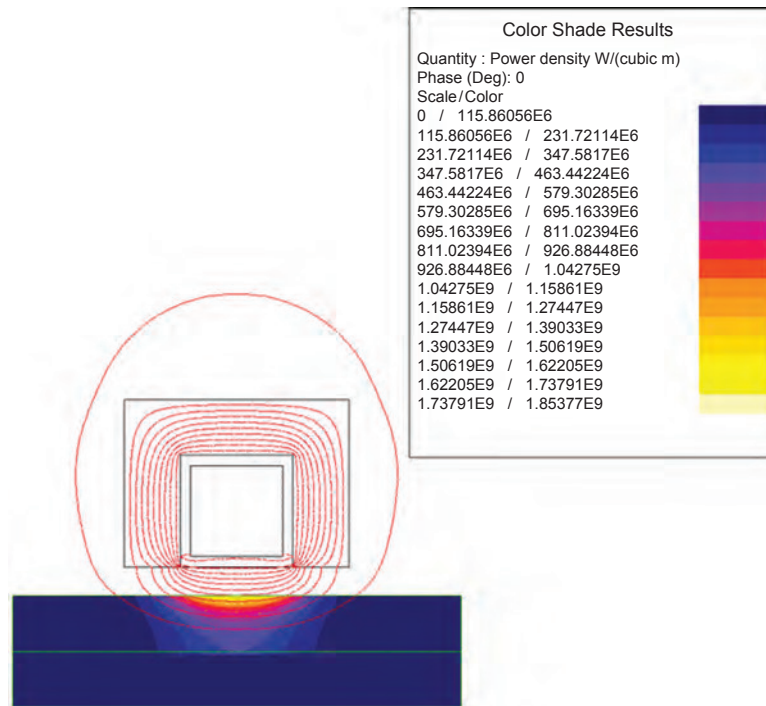


Fig. 21 Magnetic field and power density distribution for a 12.7 mm (0.5 in.) heat face with Fluxtrol A for heating of a flat plate

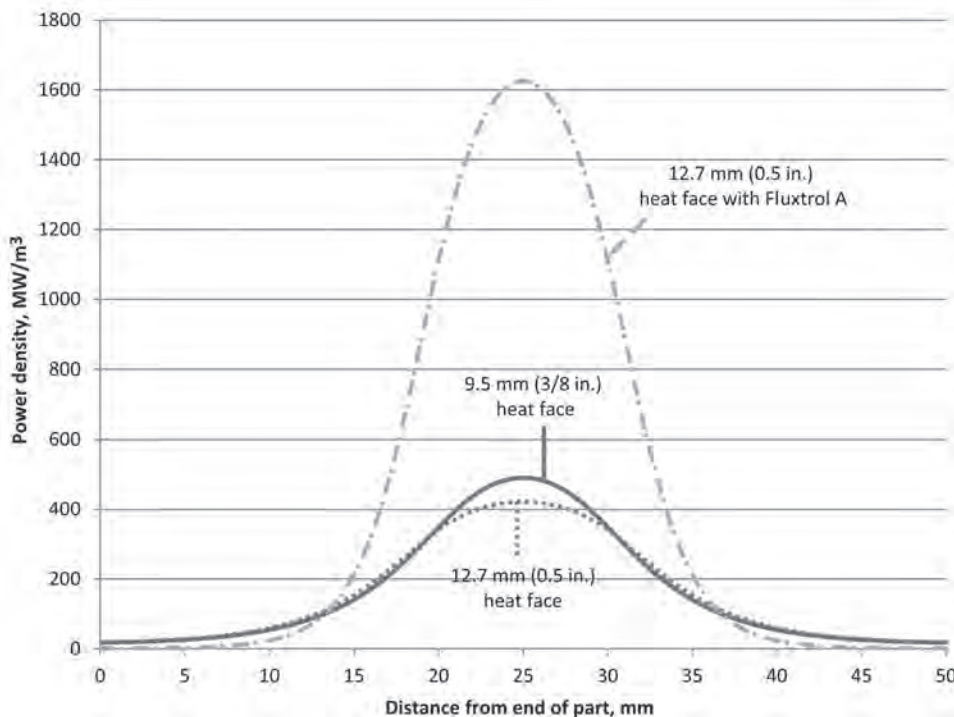


Fig. 22 Surface power density curves for all three cases of flat plate heating

interfering with the inductor; yet, to equalize the hardened pattern, some form of rotation is needed to equally heat the bearing journal on the end of the J-hook. To accomplish this, a part holder is connected to a crank and made to oscillate

through 210° during the hardening cycle, closely mimicking full rotation.

Large, heavy parts may be application specific as to their presentation to the inductor, requiring thoughtful design, materials selection,

and testing to verify the heating results. In some installations, it is necessary to present the inductor to the part. Complex designs involve robots moving the inductor along the path to be hardened. The inductor and transformer sometimes are robotically moved together, while other times, depending on the power and frequency, a flexible cable connected to the inductor may be employed. Other heating applications may use a handheld induction heating apparatus. All applications are dependent on the power required, the size of the part, and the areas to be heated.

Inductor Structure

For low-frequency and/or high-power-density induction heat treating applications, the electrodynamic forces are strong and the induction coil requires a supplemental mechanical support structure. A mechanical support structure also is required if the induction coil is heavy or manufactured from thin-walled copper tubing. Some common types of inductors where mechanical supports are used include single-shot inductors for heating shafts or stems, multiturn induction coils, induction coils without rotational symmetry, and applications where the inductor is heating a surface that is perpendicular to the buss mounting plates.

For induction heat treating coils, the mechanical support components include stud boards, retainer rings, mounting plates, and components to connect the coil to quench rings. In the vast majority of cases, the materials used for the inductor structure are made from high-temperature fiber-reinforced plastic components. In some extreme cases, such as long single-shot coils for axle shaft hardening, a fiber-reinforced stud board may be additionally supported by an aluminum housing or channel. In this case, care should be taken to insulate the inductor and any studs from the conductive support housing.

One of the more challenging induction applications that requires a strong mechanical support system is rotational crankshaft hardening with U-shaped inductors (Fig. 23). The distance from the output of the transformer to the heating area of the coil must be relatively long to ensure that the counterweights of the crankshaft will not hit the transformer. This is a challenge, because in this style of coil the electrodynamic forces are high and act in multiple directions. There also is a mechanical load placed on the induction coil, because the inductor assembly is in contact with the part during rotation.

When the crankshaft is cold, the turns are pulled toward the bearing journal and the sidewalls of the crankshaft. Once the part is above the Curie point, the forces are reversed, and the inductor is pushed away from the sidewalls and away from the bearing diameter.

Due to these multiple challenges, the structure consists of several parts. Outside the

inductor there typically are two brass or aluminum side plates. All of the components are anchored to the side plates, including the induction coil. To prevent contact of the inductor with the part, ceramic or carbide guide shoes are placed in three places (just after the ends of the loops and between the two loops) around the perimeter on both sides of the inductor. The ceramic guide shoes typically are mounted to brass or aluminum side plates.

In addition to the guide shoes, the side plates also help to keep the induction coil in position. The inductor typically is held in at least three places: the ends of each loop by a stud and G-11 component, and the leads area by a G-11 component. Other components that may be a part of the structure in crankshaft coils include leaders to facilitate the coil loading, quench heads, and side support composites to increase the rigidity of the assembly.

Coil Leads/Busswork and Contacts

With induction coils, there is an intermediate body between the coil head (the part where the induction heat treating process is conducted) and the heat station, power supply, or quick-change adapter. This section of the inductor is referred to as the coil leads or busswork. The role of the coil leads or busswork is to mechanically and electrically connect the induction coil head to the power supply. Often, the cooling water for the coil head also is supplied through the leads.

Good design practice is that the leads should be close together, with a piece of synthetic fluorine-containing resin between them to electrically separate the two leads from one another. It also is good practice to make the height of the busswork significantly longer than the length of the heat face of the induction coil.

In most cases, the coil leads or busswork must carry the same current that is in the induction coil head itself. Because the coil leads/

busswork carry a high-frequency current, the coil leads generate heat from eddy currents. The current is drawn to the side of the bussbar that faces the opposing bussbar by the proximity effect. The current density in the leads is inversely proportional to the length of the interface, and hence, the losses are approximately proportional to the length squared. The proximity of the two leads to each other primarily influences the voltage drop in the leads. The closer the leads are, the lower the inductance of the leads and hence the lower the voltage drop.

The coil contacts range from simple flared or compression fittings to machined blocks with keys to ensure location, depending on the mating surface. For heat treating environments, the machined blocks with keys are preferred for high-power-density and low- or medium-frequency environments. Compression or flared fittings should be used only in the case of high-frequency, lower-power-density applications or long solenoids with high turn numbers and low currents.

For the machined block contacts, these systems can be separated into two classes: standard bolting connections and quick-change adapters. For standard bolting connections, there are two main contact styles: fishtails or Jackson type, and flat plate. Fishtails consist of a slotted copper bar for adjustment of the vertical height, with a female key on the back to fix the horizontal position (Fig. 24a). This type of contact is common for the frequency range of 1 to 30 kHz in heat treating applications where the coil is mounted to a transformer. For this style, water typically is fed from separate water lines to the induction coil rather than through the heat station electrical contacts, because the vertical height of the coil is not always in the same place.

Flat plate contacts typically consist of a flat plate with two holes for bolts and a hole between the two bolts for water (Fig. 24b). The water-cooling hole commonly is slightly recessed for placement of an O-ring. Flat plate contacts typically are used for mounting to power supply

or heat station outputs for higher frequencies (50 to 450 kHz).

Besides bolting contacts, there are several types of quick-change adapters used in industry (Fig. 25). All of these systems involve the use of mechanical keys and a lever to press the contacts flush and fix the position of the coil in a quick motion. Coil water cooling may or may not be incorporated into the quick-change adapter. Separate water cooling typically is provided to the induction coil in the case of high power densities or where the quick-change adapter allows for a variable vertical position.

Quenching Considerations in Induction Coil Design

In many cases, quenching is done to finalize the hardening process of steel components, and it typically is done with water that has a small percentage of a quench medium. This is the second half of heat treating; this stage is just as important as heating. After the part surface is raised above the austenitizing temperature, it should be quenched (or rapidly cooled). In most cases, this should be done immediately after the austenitizing temperature is reached. The time before quenching can vary depending on the composition of the steel. The quench design must not only remove heat rapidly but uniformly as well. The results of nonuniform or slow quench are nonuniform hardness and possible overall distortion in the part (or work-piece). Nonuniform hardness can lead to premature part failure or cracking. Because of the importance of uniformity when quenching, round or symmetrical parts almost always are

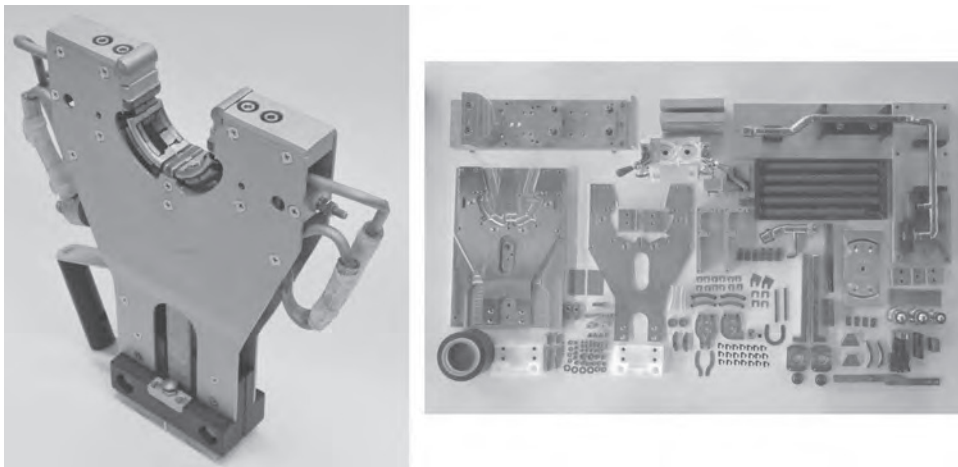


Fig. 23 U-shaped crankshaft hardening coil components and assembly

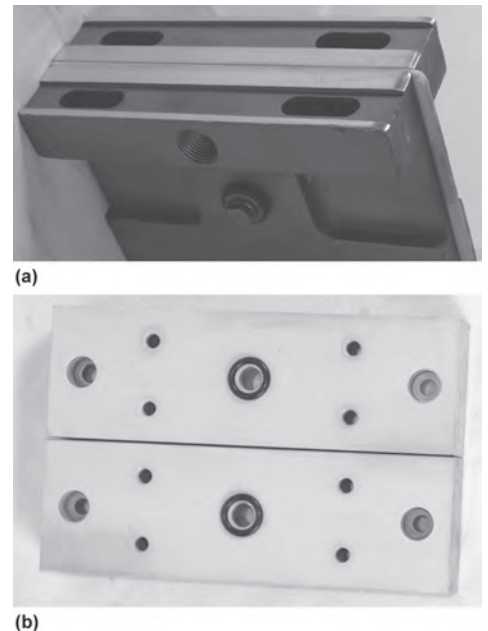


Fig. 24 (a) Fishtail-type and (b) flat plate machined coil contact types

rotated during the quenching process. Other important considerations for quench design are the part geometry and how the part is presented to the quench (i.e., horizontal, vertical, etc.). In some irregular-shaped parts, rotation is not possible, or the rotation rate is slowed to help control the quench. When quenching for surface hardness, a vigorous or intensive quench usually is required. Because of this, the quench usually is done with a series of relatively small holes. These holes usually have a staggered pattern. The small holes and staggered pattern result in an intense quenching that helps to avoid the development of steam pockets. If a submerge (or dunk) quench is used, a fine layer of steam usually is developed on the surface; this steam can act as a barrier or insulator, causing a slower quench. The size of the individual quench holes can vary from 1.5 to 5 mm ($1/16$ to $3/16$ in.) diameter, depending on the part size and geometry. It usually is desirable to keep these holes as small as possible to keep the quenching pressure higher, which helps reduce the steam pocket described earlier. This also helps to lock in the hardness by fully transforming the martensite. One disadvantage to small quench holes is that they are more likely to fill with debris or quench residue; for this reason, many quench designs for heat treating have quench holes between 2.5 and 3.2 mm ($3/32$ and $1/8$ in.) diameter.

Figure 26 shows a typical scanning quench hole arrangement. The hole size is related to the shaft or workpiece diameter, as well as a quenching area, and the air gap between the quench block and the workpiece surface (Table 2) (Ref 9).

The quench design, like the inductor design, should conform around the part. In some cases, the quench can be incorporated into the inductor design; in other cases, it is in a separate quench ring or quench block. This is further discussed in the section “Styles of Heat Treating Inductors” in this article. With regard to the duration of quenching time, quenching typically takes longer than heating; a rule of thumb is that the quench should be 1.5 the time of the heating. With static heating or single-shot heating, this can be controlled by a timer, either in the heating station or moved to a quenching station. To save cycle time, some equipment has a short quench in the heating station followed by another station to finalize the quenching process. With regard to scan heating, the quench should be designed to have direct impingement for at least 1.5 the distance of the heating face of the inductor. When scanning, the quench holes are angled away from the coil in the same direction that the part is traveling. This helps to keep the water from washing back into the inductor, and allows the water to stay on the part as long as possible.

In either case (static heating or scanning), the quenching should be done before the surface of the part falls below the hardening temperature, to ensure that the material is fully transformed.

Induction Coil Cooling

As discussed earlier, induction heating uses high currents and high power levels. Because of this, most heat treating inductors are water cooled. Some inductors are constructed of copper tubing that the water flows through. Other types of inductors are constructed from machined copper details, with cooling passages integrated within them. In either case, the passages must be designed for the intended power levels and must have maximum water flow with minimal restrictions.

Thermal degradation is caused by local or total overheating of the coil head due to eddy current losses in the copper, magnetic losses in the flux concentrator, and heat transfer from the hot surface of the part via convection and radiation. Overheating can result in copper cracking or deformation as well as concentrator material degradation. Copper cracking usually occurs in heat treating coils with a short cycle due to thermomechanical stresses, while a gradual coil deformation is more typical for continuous processes (Ref 13, 14, 18, 19). Thermal effects can strongly increase the effects of electromagnetic forces and accelerate electrical insulation aging.

Copper overheating is the leading cause of failure in heavy-loaded heat treating inductors; this section focuses mainly on this mode of failure. For consistently manufactured inductors, copper cracks occur in nearly the same place on an inductor each time in a certain range of parts produced. There are several approaches to increasing coil life: provide additional cooling, reduce the density of heat sources, or change the coil design completely.

Additional cooling can be obtained by increasing the water flow rate, reducing the water cooling temperature, adjusting the water pocket, or introducing additional cooling circuits. Water flow rate is the first step, and it is increased until the pump output limit is reached. Inductor manufacturers generally have internal guidelines related to best practices for water pocket and cooling circuit design, which have been developed over the years (Table 1). These guidelines generally are based on frequency and power density. Once these standard options have been exhausted, the next step is to replace the existing pump with a larger one or to introduce a booster pump to the system.

Sometimes on very high-power-density coils, a limit is reached where, even with the best cooling circuit design and very large pumps, coil lifetime is still unsatisfactory. At this point, it is necessary to try to minimize the localized power density in the weak point of the inductor. This often is challenging in complex inductors,

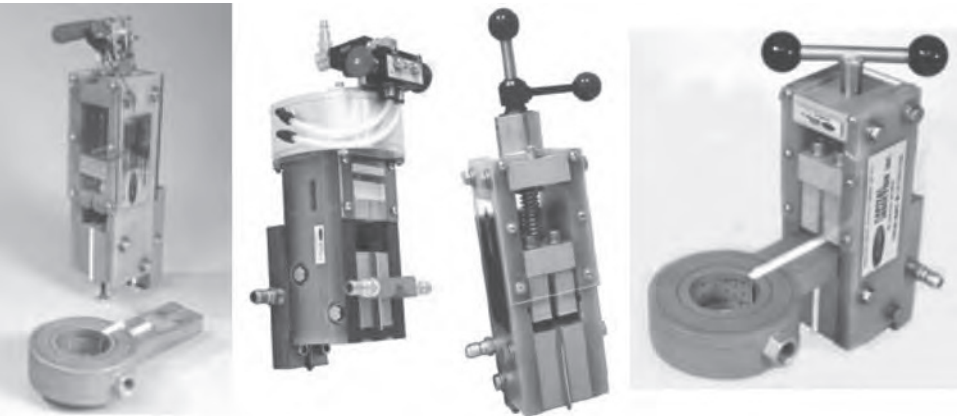


Fig. 25 Styles of quick-change adapters. Courtesy of Capital Induction

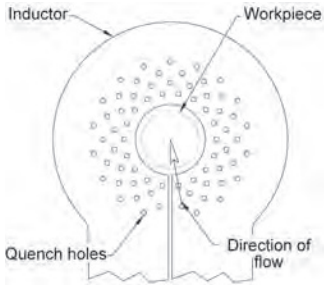


Fig. 26 Quench hole arrangement for scanning coil. Source: Ref 9

Table 2 As workpiece diameter increases, orifice size should increase to help provide a more uniform quench

Shaft diameter		Orifice size	
mm	in.	mm	in.
6.5–13	0.25–0.50	1–1.5	0.046–0.063
13–38	0.50–1.50	1.5–2.5	0.063–0.094
>38	>1.50	3.5–4	0.125–0.156

Source: Ref 9

because changing this section may have some effect on the heat pattern in this area of the part, as well as in the rest of the part.

To determine what high power density is, it is important to consider the cause of the failure. The failure mode that can be resolved with water cooling in high-power induction heat treating coils is mechanical fatigue caused by thermal cycling. During each heat treating cycle, the copper temperature rises as the power is turned on, primarily due to current in the induction coil. As the copper temperature increases, the copper expands. When the power is turned off, the copper rapidly cools and contracts.

Because the eddy currents are distributed non-uniformly in the copper cross section, the temperature distribution in the copper coil is also nonuniform. Water in the induction coil removes heat through forced convection. This means that the rate of heat removal is directly proportional to the heat-transfer coefficient and the temperature difference between the copper and the bulk water. The heat-transfer coefficient depends on the velocity of the water, the pressure of the water (in addition to the effect of pressure on water flow), and the temperature of the water.

In recent years, computer simulation has proven an effective tool for estimating thermal cycles in induction coils during a heat treating process (Ref 19–21). These recent studies were made using some combination of electromagnetic, thermal, and fluid dynamics codes or correlations. With this method, the temperatures that are the source of the dimensional movement and stress are predicted. Certain guidelines for maximum allowable temperatures are used to ensure good life. It is envisioned that in the future, these codes could be coupled with structural, stress, and distortion simulation.

Case Study: Single-Shot Coil Copper Temperature Prediction

A case study using computer simulation to show typical temperature distributions in a single-shot induction hardening coil is discussed in this section. Flux 2D is used for electromagnetic and thermal simulation, and analytical calculations are made for the heat-transfer coefficients. The influence of pressure (high and low), wall thickness (1, 1.5, and 3 mm, or 0.048, 0.062, and 0.125 in.), current in the coil (5,000, 7,500, and 10,000 A), and frequency (1, 3, and 10 kHz) is considered. The correlations for heat-transfer coefficient hold only to approximately 250 °C (480 °F) on the interface of the copper wall with the cooling water, so if this consideration is not met, the temperature in the coil will be less accurate.

The geometry for the study is a 19 mm (¾ in.) square copper tube with Fluxtrol A magnetic flux concentrator for heating of a 38 mm (1.5 in.) diameter shaft. The coupling gap used for the study is 3.2 mm (⅛ in.). To limit the number of variables, the part is not simulated during the study. The part is approximated by

a nonmagnetic layer 6.3 mm (¼ in.) thick, with the properties of steel above the Curie point and the 25 mm (1 in.) diameter core, which has the properties of cold low-carbon steel.

Figure 27 shows the temperature distribution in the coil cross section if the current is 5000 A at 10 kHz with low pressure and a wall thickness of 1 mm (0.048 in.) after 10 s of heating. The temperature is highest in the corners of the heat face and somewhat lower in the center of the turn. The concentrator is at a significantly lower temperature, and the localized higher-temperature areas are due to conduction through the glue to the concentrator. The maximum temperature is 117 °C (243 °F). Figure 28 shows the temperatures in the corner and center of the tube versus time for this case. Nearly the entire temperature rise in the copper occurs in the first 2 s.

If pressure is doubled, the temperature distribution is that shown in Fig. 29(a). The maximum temperature in the corner is reduced to 99 °C (210 °F). The difference between the temperature in the corner of the copper and the center of the heat face is significantly higher. Figure 29(b) shows the temperature distribution if the wall thickness is increased to 1.5 mm (0.062 in.). The maximum copper temperature is slightly higher, 102 °C (216 °F). If the wall thickness is increased to 3 mm (0.125 in.), the maximum temperature increases to approximately 111 °C (232 °F) (Fig. 29c).

All of these temperatures are what could be considered reasonable, and a long copper

lifetime would be expected based on the temperatures. If the current is increased to 7500 A, the differences between the results are much more apparent. Figure 30 shows the temperature distributions for the same cases shown in Fig. 27 and 29 with the higher current. Now the temperature of the copper wall contacting the water for the low-pressure, 1 mm (0.048 in.) wall (Fig. 30a) is above the threshold where the correlations hold. This means that there is danger of vapor blanket formation and very short coil lifetime. It also is important to note that the maximum temperature shifts to the center of the tube instead of the corners. This is a sign that there is insufficient cooling, and increasing the water pressure can significantly increase the coil lifetime.

When pressure is increased, the temperature on the internal walls of the copper tubing drops to manageable levels (Fig. 30b). The maximum temperature again is in the corners of the copper tube instead of the center. However, the level of the copper temperature in the corners remains elevated (225 °C, or 437 °F). For the thicker walls, the temperatures are 230 and 263 °C (446 and 505 °F), respectively (Fig. 30c, d).

This means that in each cycle, the copper in the corners of the tubing expands more than twice as much as for the case of the lower current. When power is turned off, the tubing contracts to its original shape. At these temperatures, there is the potential that the coil lifetime may not be satisfactory.

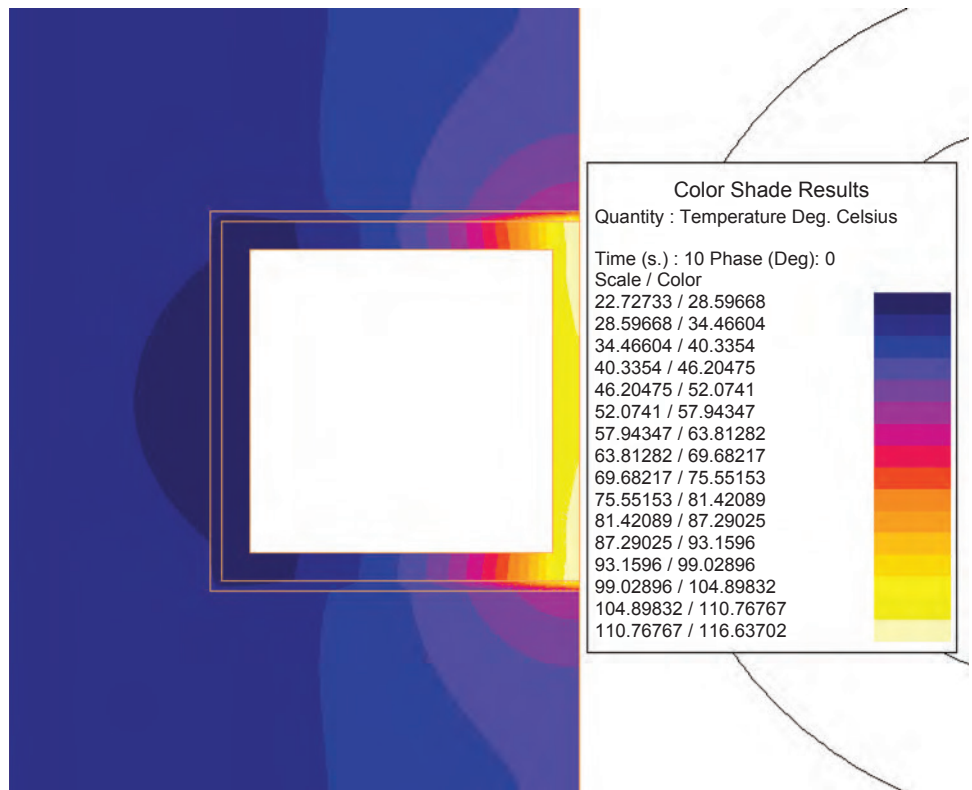


Fig. 27 Temperature distribution in the induction coil with 1 mm (0.048 in.) wall thickness, 10 kHz frequency, 5000 A current, and low-pressure cooling

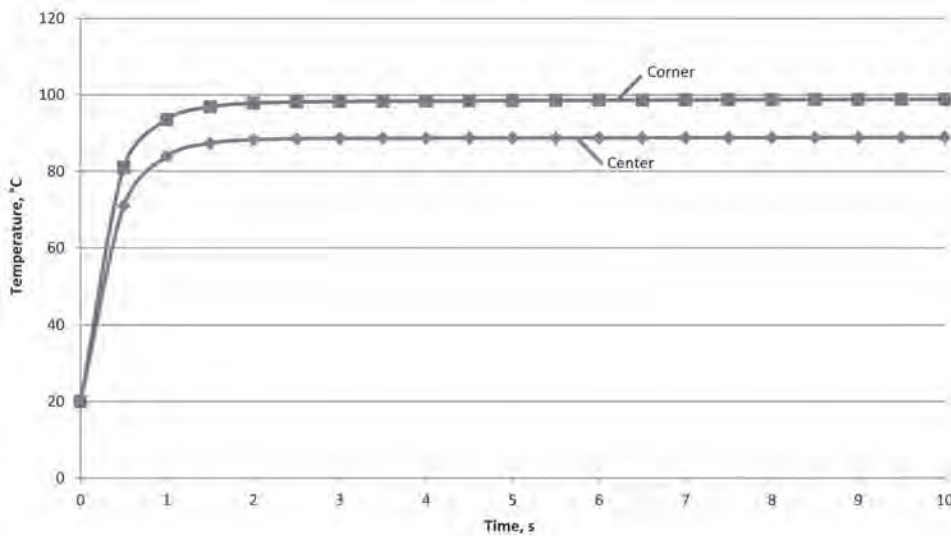


Fig. 28 Temperature dynamics during heating at critical points with 1 mm (0.048 in.) wall thickness, 10 kHz frequency, 5000 A current, and high-pressure cooling

If frequency is reduced but the current remains 7500 A, the coil temperatures are reduced significantly (Fig. 31). For the case of the 1 mm (0.048 in.) wall with low pressure, the maximum temperature is reduced to 178 °C (352 °F) (Fig. 31a). The temperature in the corners is significantly lower than in the center. If pressure is increased, the copper temperature is reduced to 133 °C (271 °F) (Fig. 31b). However, the maximum temperature is still in the central sections of the copper rather than the corners. This is due to the wall thickness of the copper being less than optimal (1.6δ). The low copper thickness increases resistance and losses in the central section of the coil.

When the wall thickness is increased to 1.5 mm (0.062 in.), the copper temperature is reduced to 114 °C (237 °F) (Fig. 31c). The central temperature of the winding also is reduced relative to the corners. The maximum in temperature lies just inside the edge of the water cooling, implying slightly less than optimal wall thickness. For the case of the 3 mm (0.125 in.) wall, the maximum temperature goes up again to 125 °C (257 °F) (Fig. 31d). The maximum now is clearly in the corners. The temperature in the center of the tube actually is lower for this case. The rise in maximum temperature is due to it being a farther distance from the water cooling.

The losses in the copper tubing are nearly the same for these two cases (3 kHz; 1.5 and 3 mm, or 0.062 and 0.125 in., wall thickness) and just under 20% lower than for the 1 mm (0.048 in.) wall thickness. The optimal wall thickness and hence the maximum current-carrying capacity for 3 kHz would lie between these two thicknesses.

At 1 kHz, 10,000 A was used for comparison, because at lower frequencies it is natural to have higher currents (Fig. 32). For the 1 mm (0.048 in.) wall thickness and low pressure, temperature in the copper clearly is excessive, and there is a significant gradient from the center to the corners (Fig. 32a). As pressure is

increased, the temperature is marginal (230 °C, or 446 °F, wall temperature), and there is still a significant gradient from center to edge (Fig. 32b). This is because the wall thickness is significantly less than optimal.

For the 1.5 mm (0.062 in.) wall thickness, the maximum temperature declines to approximately 144 °C (291 °F) (Fig. 32c). Losses in the copper are nearly 40% lower than for the 1 mm (0.048 in.) wall thickness. The temperature distribution across the face is nearly flat, implying that the wall thickness is less than optimal. For the 3 mm (0.125 in.) wall thickness, the maximum temperature is only 100 °C (212 °F), and the location is the corners (Fig. 32d). The losses in the 3 mm (0.125 in.) wall thickness are approximately 30% lower than for the 1.5 mm (0.062 in.) wall thickness.

Another factor related to water cooling of induction coils is the water temperature. The temperature of the induction coil is influenced in two ways by the water temperature. It is clear that the lower the water temperature, the cooler the induction coil, because the cooling method is convection. If the water temperature was lowered by 10 °C (18 °F), then it would be expected that the maximum temperature in the copper also would be 10 °C (18 °F) lower.

Because the temperature change (ΔT) of the copper would be the same, one would expect that the magnitude of the copper movement would be the same, and coil lifetime would be also. However, this is not true, because the coefficient of thermal expansion of copper is not constant with temperature (Fig. 33). As temperature rises, the coefficient of thermal expansion of copper continues to rise (Ref 22). This means that the higher the temperature, the larger the movement for the same ΔT .

In reality, the ΔT of the copper is not the same. It actually is slightly less, because the copper electrical resistivity rises with temperature. Therefore, the losses in the copper are lower, and the resulting ΔT smaller. This overrides the

fact that the heat-transfer coefficient of water is slightly lower at lower temperature (Ref 23).

The last factor to consider with water cooling of inductors is the water quality. The best fluid for cooling induction coils in heat treating applications is pure, demineralized water. Pure water has a naturally high heat-transfer coefficient. Almost all additives have a negative effect on the heat-transfer capability.

Minerals are especially bad. Over time, they tend to fall out of solution and build up on the wall of the copper tubing. This has two negative effects. First, the mineral layer reduces the cross section for water flow. The mineral layer also creates a barrier for heat transfer, causing the temperature of the copper to rise. If water containing minerals is used, over time the copper temperature continues to rise and reach a critical level, resulting in an inductor failure. With this type of cooling fluid, the induction coil must be cleaned and flushed on a regular interval.

Styles of Heat Treating Inductors

As stated previously, induction heat treating coils come in many shapes and sizes. An excellent source for photos of induction heat treating coils is the book *Practical Induction Heat Treating* by Richard Haimbaugh (Ref 5). These photos are included in *Steel Heat Treating Fundamentals and Processes*, Volume 4A of *ASM Handbook*, 2013, so they are not repeated here.

Skills for Heat Treating Inductor Construction

Copper is a unique metal associated with an ancient skills trade—coppersmithing. While training as either a craftsman or an artisan, a student coppersmith would apprentice under a journeyman to learn the character and manipulation of this metal. Although the United States has assimilated the coppersmith into other skilled trades, coppersmithing is still a recognized trade throughout the industrialized world.

The tools and skills of a coppersmith are ideally matched to the metal; however, is a coppersmith by trade needed to build a copper inductor? The answer is no; yet, the skills of a coppersmith must be learned in the process of building heat treating inductors, along with a familiarity of high-power electrical circuits.

Basic Skills

Because copper has a characteristic of being easily formed into complex shapes, a craftsman handy with tools, a soldering iron, and a propane torch is able to build a good basic inductor. In the process of forming, copper work hardens; yet, when heated to a dull red and quenched in water, it again forms easily. Basic inductors are made of readily available copper tubing wound

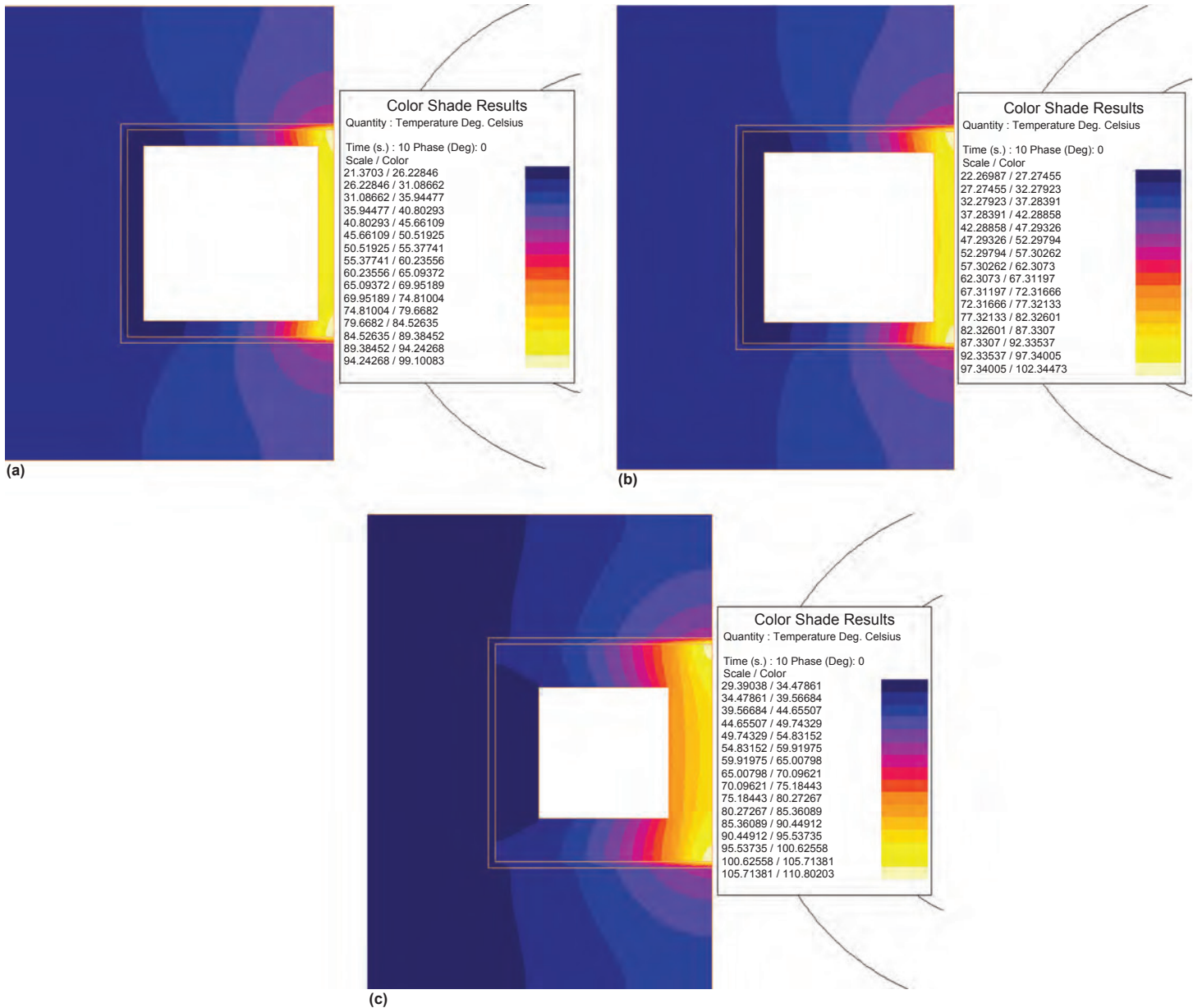


Fig. 29 Temperature distribution in the induction coil with wall thicknesses of (a) 1 mm (0.048 in.), (b) 1.5 mm (0.062 in.), and (c) 3 mm (0.125 in.) with 10 kHz frequency, 5000 A current, and high-pressure cooling

around a forming mandrel. Copper tubing provides a convenient path necessary to cool the copper. Depending on the induction power supply configuration, simple electrical connections may be brass pipe fittings—either flair or compression, although flair is preferred—or copper tabs that are soldered to the tube, as mentioned previously. Electrical soft solder is sufficient at power requirements of 10 kW or less.

Advanced Skills

A classically trained machinist is the usual tradesman employed to build heat treating inductors. A suitable candidate has the ability, dexterity, and patience for modelmaking. Most

will have difficulty machining copper unless instruction is provided in the use of special cutting tools, speeds, feeds, and coolant specific to this metal. Much of the work in building complex inductors involves a quantity of small parts and various materials that require machining, forming, silver brazing, and assembly. Heat treating inductors usually are built one at a time, and one machinist may do all of the work. A simple machine shop consisting of a floor model milling machine, lathe, band-type table saw, a ventilated brazing table with torches, and assembly bench with a variety of hand tools makes a suitable work area.

Most inductors are best built from design prints. A good print package has a bill of material,

details of all components, and an assembly and inspection form. In some cases, the inductor may be built by reverse engineering the original. The following should be considered during the construction of heat treating inductors:

- **Machining:** Most of the raw material in a typical heat treating inductor is in the form of electrolytic copper sheet, plate or round. Due to the gummy nature of the metal, cutters, feeds, speeds, and coolant specifically designed for copper are advised for milling, drilling, and turning operations.
- **Fabrication:** Many parts may be needed to complete a heat treating inductor assembly. Some of these parts are fit to provide

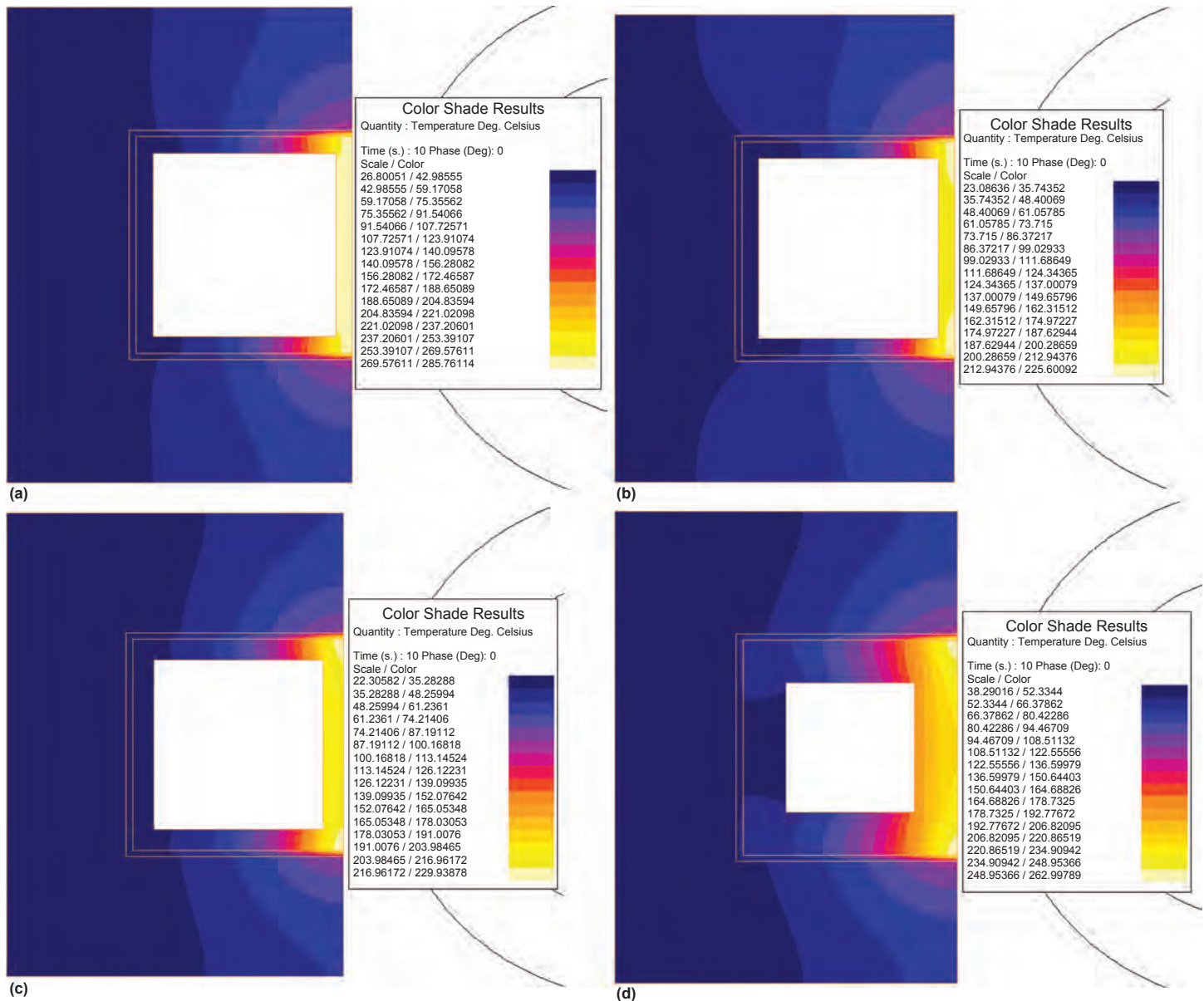


Fig. 30 Temperature distribution in the induction coil with (a) 1 mm (0.048 in.) wall thickness, 10 kHz frequency, 7500 A current, and low-pressure cooling; (b) 1 mm (0.048 in.) wall thickness, 10 kHz frequency, 7500 A current, and high-pressure cooling; (c) 1.5 mm (0.062 in.) wall thickness, 10 kHz frequency, 7500 A current, and high-pressure cooling; and (d) 3 mm (0.125 in.) wall thickness, 10 kHz frequency, 7500 A current, and high-pressure cooling

covers for cooling chambers and ancillary connections that involve cooling or quench or both. Integrity of fit is necessary to provide watertight and quality electrical connections.

- **Silver brazing:** While some fuel gases are best suited for silver brazing, choosing an appropriate fuel, such as methyl-acetylene-propadiene gas, to mix with compressed oxygen may be subject to limited availability. Torch heat must be sufficient to maintain silver brazing temperatures throughout the copper mass. A variety of torch tips are needed, along with flux and 1.5 mm (0.06 in.) silver brazing rod. The silver content of the brazing rod best suited for inductor construction is at 5 to 45%. Silver brazing is a skill

that can be difficult; however, with practice, patience, and perseverance, the technique can be mastered.

Repair Skills

Copper inductors sometimes are subjected to the extreme conditions of induction heat treating: electromagnetic stress, intense heat, oily smoke, steam, dirt, and grime. The effects on copper can be severe, resulting in deterioration and fatigue of the inductor and, ultimately, the heat treating process. Inductor maintenance is essential. Cleaning the inductor with soap, water, and a soft plastic brush, along with regular inspection of the copper and components,

alerts the induction operator to deterioration and performance issues.

Repair skills are advanced. The inductor is cleaned, disassembled, and inspected for deterioration of copper as well as for leaks and cracks. Cosmetic repairs such as straightening bent components usually can be made without annealing the copper. Ancillary components such as flux intensifiers, brackets, guides, and quench units are cleaned and inspected for damage and are repaired or replaced.

Cracks in a copper inductor can result from any of the following: cyclic fatigue, differential cooling of the copper, resistive braze joints, and abuse. Cracks often are repaired with silver braze. Although this patch may be a

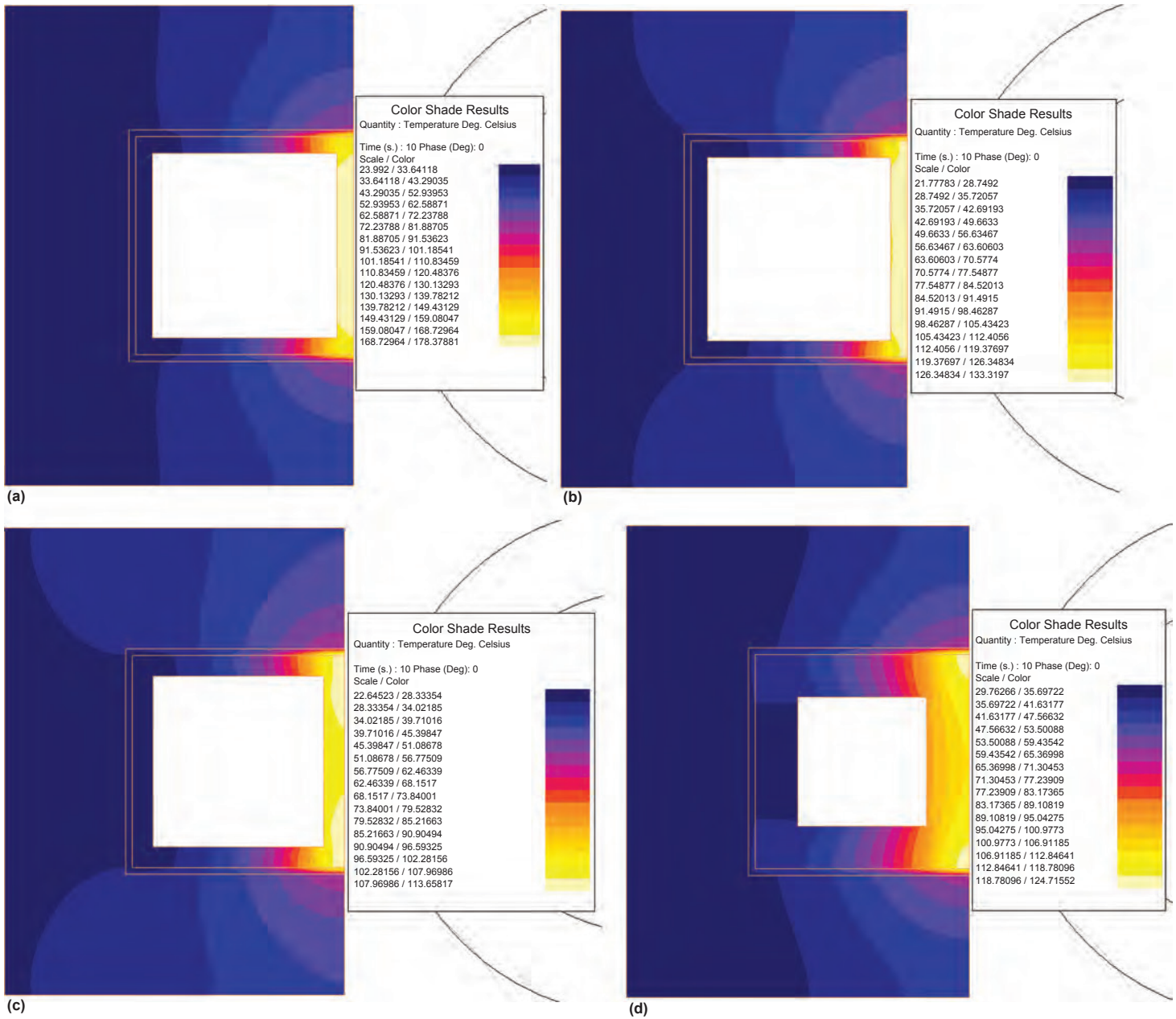


Fig. 31 Temperature distribution in the induction coil with (a) 1 mm (0.048 in.) wall thickness, 3 kHz frequency, 7500 A current, and low-pressure cooling; (b) 1 mm (0.048 in.) wall thickness, 3 kHz frequency, 7500 A current, and high-pressure cooling; (c) 1.5 mm (0.062 in.) wall thickness, 3 kHz frequency, 7500 A current, and high-pressure cooling; and (d) 3 mm (0.125 in.) wall thickness, 3 kHz frequency, 7500 A current, and high-pressure cooling

cost-effective repair, it is seldom permanent. In a robust process, the copper inductor should be replaced at an appropriate time/life interval.

Attachment of Magnetic Flux Controllers

It has been explained that flux controllers are needed to direct the current flow for specific induction heating applications. Attaching them to the inductor requires careful handling so that they are properly placed and secure.

Misplacement or loss of any portion of a magnetic flux controller may result in a nonconforming processed part. Magnetic flux controllers are frequency dependent and made from either a silicon steel, soft magnetic ferrite, or a soft magnetic composite. Attaching these materials to an inductor can present a challenge to the designer/builder. The following are a few examples.

Silicon Steel Laminations

This material is supplied in a variety of grades, thicknesses, and finishes. Its usual form is a thin sheet with an insulating layer on both

sides. It is first designed to a specific shape, then die stamped or machined and to fit the inductor. The most common shape is a rectangular or square "C" form. The laminations are stacked side by side onto the inductor in such a way as to expose that portion of the copper to the part being heated. Copper tabs of the same shape are silver brazed onto the inductor at various intervals in order to support the stack. Securing the stack is achieved by either gluing with a high-temperature epoxy or by mechanically clamping it to the inductor. Various clamping methods are used. The most common is the use of a semirigid glass epoxy circuit board

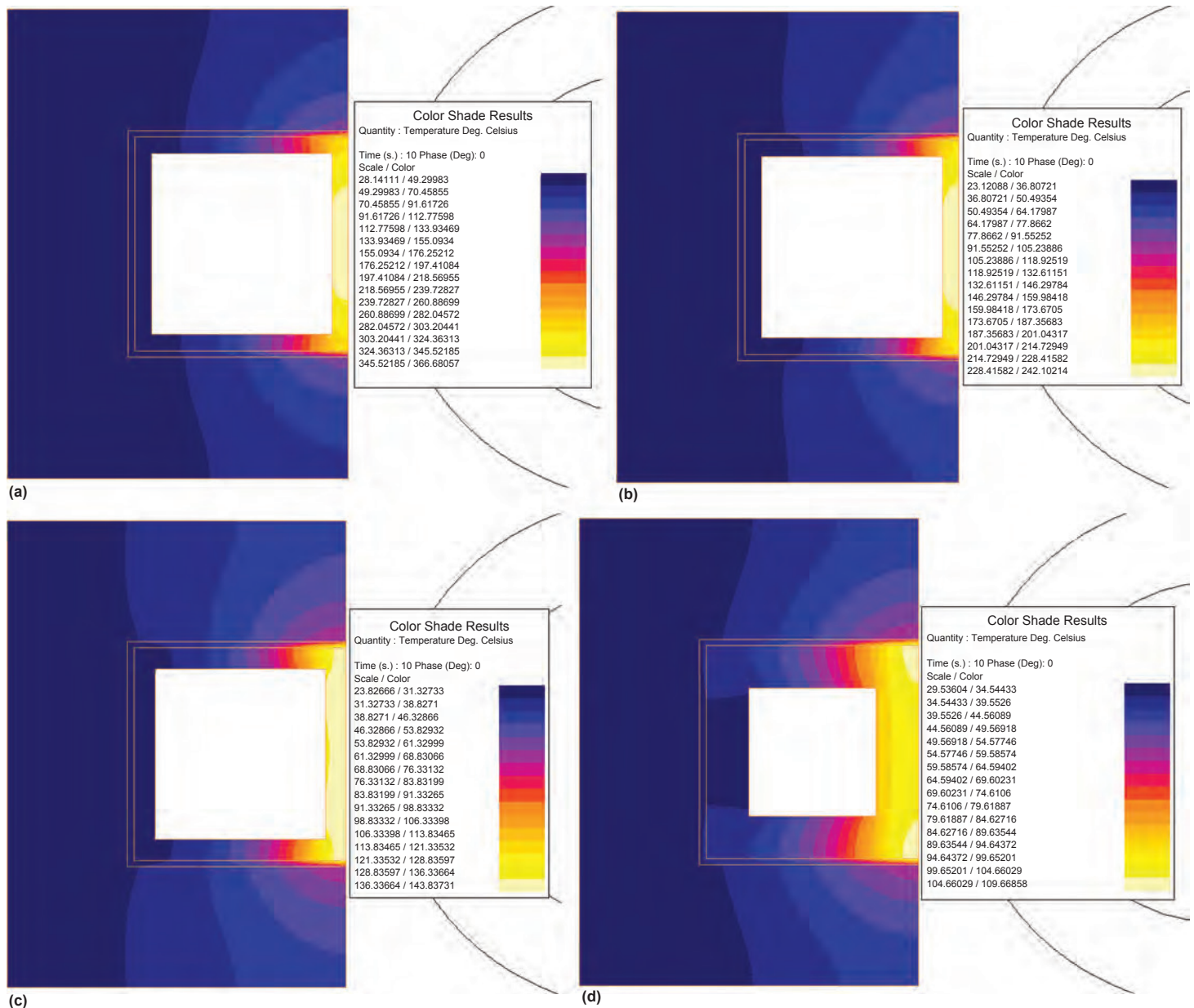


Fig. 32 Temperature distribution in the induction coil with (a) 1 mm (0.048 in.) wall thickness, 1 kHz frequency, 10,000 A current, and low-pressure cooling; (b) 1 mm (0.048 in.) wall thickness, 1 kHz frequency, 10,000 A current, and high-pressure cooling; (c) 1.5 mm (0.062 in.) wall thickness, 1 kHz frequency, 10,000 A current, and high-pressure cooling; and (d) 3 mm (0.125 in.) wall thickness, 1 kHz frequency, 10,000 A current, and high-pressure cooling

material, such as G-10, that is cut and fit to the back of the stack and is fastened at both ends. It is practical to stack laminations around the outside or inside of an inductor loop. Installed onto circular inductors, the laminations radiate from the center point, leaving noticeable gaps, especially on small, circular inductors; yet, with careful design, this can be minimized.

Soft Magnetic Composites and Sintered Ferrites

These products are engineered and manufactured for specific induction applications. Because

sintered ferrites are brittle and difficult to machine, their use mainly has been limited to transformer applications. Soft magnetic composites, however, have been designed specifically for the induction heating industry. These products are engineered to be used at the common power-supply frequencies. They are manufactured in various block sizes, are easily machined, and fit to the inductor. Both iron ferrites and soft magnetic composites are attached to the inductor, either mechanically with bolts and screws or with glue. The product literature describes their use in induction heating applications (Ref 13).

Integrity Procedures prior to Production

This section includes discussion on flux and oxide removal, leak and flow checking, silver plating, and electrical parameter measurement.

Flux and Oxide Removal

After brazing, the induction coil copper has flux near the braze joints, along with oxidation from the high-temperature brazing process. Prior to assembly, the flux and oxides should be removed.

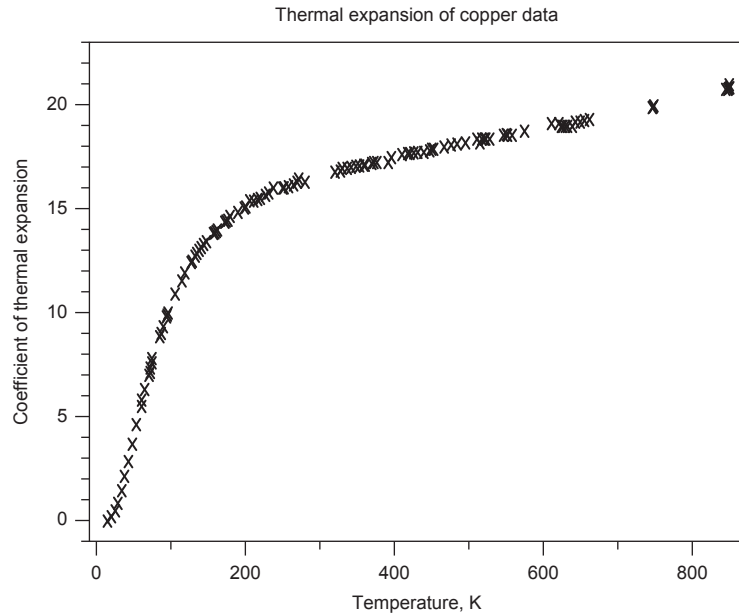


Fig. 33 Temperature dependence of the coefficient of thermal expansion of copper. Source: Ref 22

The first step in the process is to place the induction coil under hot (70 to 80 °C, or 150 to 180 °F) running water. Hot water helps to remove the bulk of the flux remaining from the brazing process. It also is recommended to flow the hot water through the water-cooling passages of the inductor to remove flux that could be built up on the inside of the tube and obstructing the passage.

After the hot water cleaning, the next step in the process is to sandblast the inductor to remove the oxides. The sandblasting process also removes the remaining flux from the inductor. After sandblasting, a fine glass beading process should be used to improve the surface condition of the inductor.

After glass beading, the copper is clean. If left this way, the inductor oxidizes in air and change color. It is good practice to spray the surface of the induction coil (with the exception of the electrical contacts) with a clear coat varnish. The varnish inhibits copper oxidation.

In some cases with heavily loaded heat treating inductors, a low-temperature tempering at 200 °C (400 °F) for several hours or a higher-temperature annealing process in air is performed. This tempering process removes the stresses from manufacturing and oxidizes the copper to a dark orange (tempering) or a dark brown (annealing). From this state, the copper does not oxidize further, and it is not necessary to apply a clear coat varnish.

Leak and Flow Checking

After cleaning the induction coil, it is necessary to ensure that it is leaktight and that the water passages are not clogged. Leak checking of the induction coil typically is done by submerging the induction coil in a tank of water

and applying high-pressure shop air. The test should be conducted for several minutes. If bubbles appear, the coil must be sent back to the coil builder to repair the leak. In some special atmosphere heat treating applications, a water leak is especially dangerous. In these instances, helium leak checking should be performed.

After leak checking, the induction coil should be connected to water lines. With a specific pressure applied, the flow rate of the water through the induction coil should be measured. For every induction coil, a minimum flow rate should be defined. If the flow rate does not meet this minimum level, it means that the cooling channel is obstructed. The obstruction must be removed before the induction coil can be shipped; therefore, the induction coil should be sent back to the coil builder.

Silver Plating

Silver plating of the induction coil contacts typically is done after cleaning. The main role of silver plating is to act as a corrosion inhibitor for the electrical contacts. Corrosion increases the contact resistance and can lead to premature induction coil failure.

Silver plating materials can come in liquid, paste, or powder form. Liquid silver plating solution from HM Products Inc. is most commonly used in the trade. The solution is either brushed or rubbed onto the contact area. After application, the contact area is flushed with water. If the surface is not flushed with water shortly after application, the silver carrier corrodes the contacts, and a green oxide formation occurs. Care should be taken while using the silver plating materials, because most of them contain sodium cyanide, which is a toxic material.

Electrical Parameter Measurement

On some induction coils, such as cast or potted inductors, it is not possible to physically see or mechanically inspect all of the critical dimensions of the induction coil. Also, on induction coils with magnetic flux controllers, it is not practical to count the number of laminations, or it may be difficult to determine if the correct soft magnetic composite material grade was used.

To ensure that the induction coil performance is consistent with other induction coils built to that print, coil electrical parameter measurements should be made prior to shipping. The best inspection method involves measuring the inductance or impedance and the resistance of the induction coil with the component it is designed to heat at the frequency of the heating. If this is not possible, valuable information can be obtained about the coil consistency from a measurement of the inductance without a part.

Devices capable of measuring coil inductance or impedance and resistance (LCR meters) at a selectable frequency typically cost several thousand dollars and are available from a number of manufacturers. For inductance measurement only, less-expensive devices are available. At the time of this writing, one such device that works well, the L/C Meter IIB, is manufactured by Almost All Digital Electronics and costs under \$200 (Ref 24). Over time, new devices will come to the market with even better characteristics for induction coil quality control.

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