To more easily wrap the copper tube around the mandrel, it generally is annealed to a bright-red temperature and cooled in water during the fabrication process. The annealing of the copper tube both prevents fractures in the tube as well as makes it easier to form. Copper tubing typically is annealed in the temperature range of 370 to 650 °C (700 to 1200 °F).

To form some sizes of tubing around the work mandrel and to form them to the proper diameter in shape without deformation, the copper tube is filled with a low-temperature alloy, sand, or buckshot to prevent the collapse of the tubing. This technique rarely is required on the larger induction coils that use large, heavy-wall copper tubing and have large-diameter windings. It is, however, necessary on small applications generally used at higher frequencies. It also can be helpful when winding a very tightly wound coil designed to heat small-diameter products.

Fig. 9 Induction forge coil electrical insulation

Induction Coil Electrical Insulation

The induction forge coil winding must be properly insulated with a suitable electrical insulation material, as shown in Fig. 9.

This is one of the many important factors that will help to make a coil last longer between rebuilds in any given application. The electrical insulation must be high dielectric, high temperature, and somewhat flexible to withstand the flexing necessary to both place the coil winding into the enclosure and absorb the operational frequency on open style and in low-frequency-application designs. The electrical insulation also must be uniformly applied. The electrical insulation should be designed to provide a continuous, tough moisture- and chemical-resistant dielectric coating. Some manufacturers simply paint or varnish coat the coil winding. This method, while providing the required dielectric properties, does little to enhance the overall life of the coil. The use of electrostatic sprays (Fig. 10), fluidized beds (Fig. 11), and electrostatic fluidized beds allows the use of better electrical insulation materials with the ability to increase the thickness applied. Higher-end fusion blend process insulation materials ensure that each individual particle of powder contains all of the components necessary to facilitate a complete cure and attain stated performance properties. Many of these insulation systems can be applied either cold and then placed into an oven for curing, or hot with the coil preheated in the range of 205 to 230 °C (400 to 450 °F). When applied to a hot part, the resin melts, flows to a controlled extent, then cures, bonding to the substrate and coalescing into a smooth, continuous, essentially uniform, thick dielectric coating. The continuous temperature-use range varies widely for each manufacturer and for the material used for this insulation coating process. The varnish at the low end has a continuous-use temperature of 200 °C (390 °F), and the higher-end materials feature continuous-use temperatures of 340 °C (645 °F) or higher. The use of an insulation system with the highest possible dielectric strength, cut-through resistance, highest possible temperature-use range, excellent edge coverage—all combined with the ability to place it onto the coil winding with uniform thickness—will help to make the induction coil less likely to fail from a short-to-ground failure. It also will help to minimize nuisance ground-detection faults.

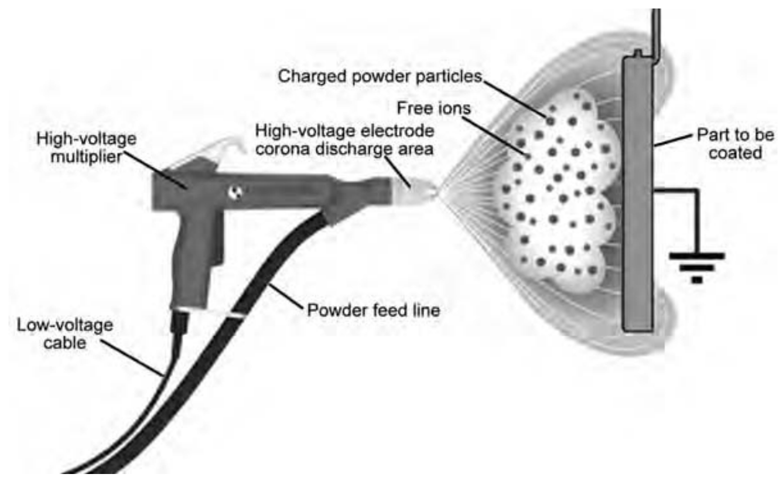

Fig. 10 Typical function of the electrostatic powder application gun

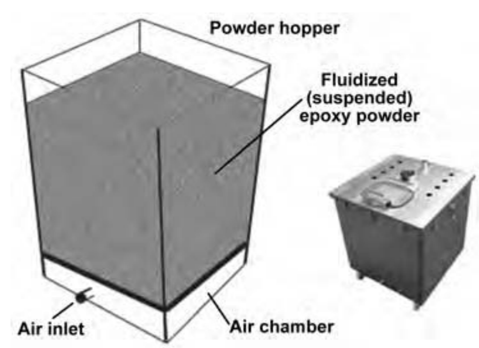

Fig. 11 Typical components of a fluidized-bed system used to powder coat the coil windings to provide a high-dielectric insulation on the winding

Mounting and Securing the Induction Coil Winding

During normal operation of a forge coil, forces between the load and the coil winding due to the electric current flowing in both can be rather large and may result in movement of the coil winding. The coil winding must be attached, contained, or supported in a method to secure it and prevent it from moving. In very-low-frequency applications, the coil winding actually is compressed between the two end plates of the coil to prevent it from moving and vibrating (Fig. 12, 13). If the coil winding is allowed to move in these applications, the copper eventually will work harden, and failure will occur. The studs that run between the two end plates which hold the coil in compression in low-frequency applications must be electrically isolated so that recirculating currents are not set up.

On medium- to higher-frequency applications, it also is important to secure the winding.

This often is done with studs attached to the side of the coil windings, which then bolt through a rigid fiberglass board. Coil windings of this design then can be either cast solid or feature replaceable coil liners. In some designs, wood support boards are positioned on three or four sides of the coil winding to lock the winding into place. The refractory then is grouted into place, filling the voids between the windings. A very simple and cost-effective design can include a complete monolithic all-cast coil that locks the winding into place via the refractory encapsulation. Two versions of this design are seen in Fig. 14 and 15.

There are many types of boards used to support the coil windings and to form end caps on induction coils. Early on, the coil end boards were made from an asbestos material until it was removed due to safety reasons. This material was replaced with an interim material that was inferior both mechanically and thermally. Since then, several manufacturers have developed what is referred to as refractory sheet materials (Fig. 16). These materials are very expensive compared to the asbestos replacement material; however, they have more strength and can withstand temperatures up to 1260 °C (2300 °F). Electrically, they are nonconductive and can be used nearly anywhere in the design of an induction coil.

Cast refractory end plates reinforced by stainless steel needles mixed into the refractory were developed to help lower the cost of

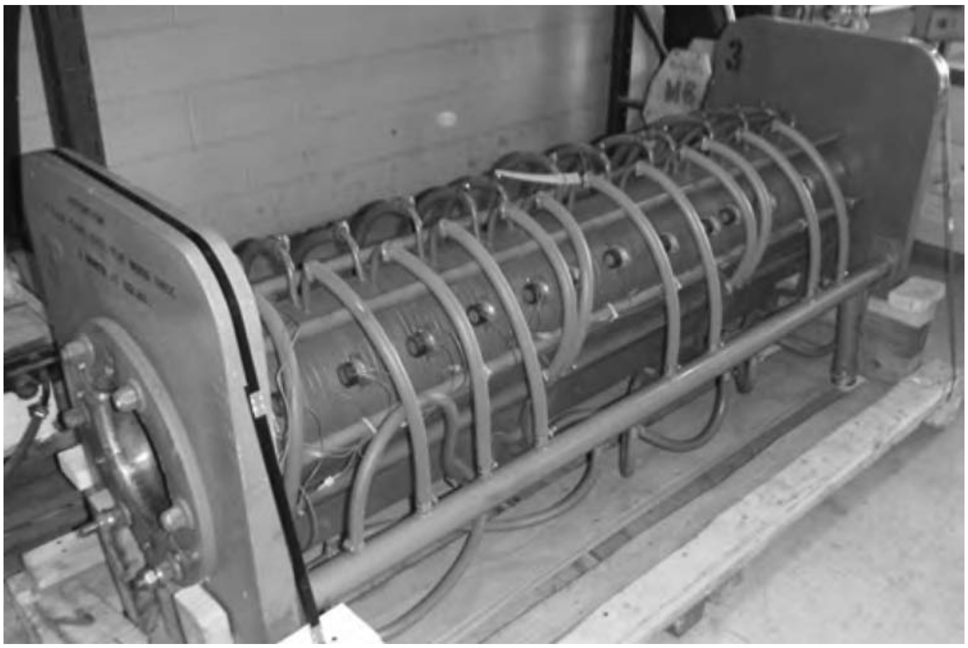

Fig. 12 Low-frequency coil design in which the induction coil winding is compressed between end plates using long rods with threads and nuts. Courtesy of Ajax Tocco Magnethermic

Fig. 13 Low-frequency coil design in which the induction coil winding is compressed between end plates

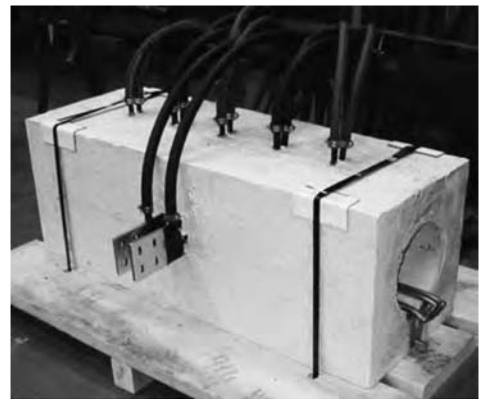

Fig. 14 Monolithic all-cast block coil used to heat bars and billets. Courtesy of Ajax Tocco Magnethermic

Fig. 15 Monolithic all-cast channel or conveyor coil typically used to heat bar ends for warm and hot forging applications. Courtesy of Ajax Tocco Magnethermic

Fig. 16 Grouping of various sizes, thicknesses, and grades of refractory sheet materials used in fabrication of induction coils

end-plate replacement in many applications that use very thick coil end boards. The manufacture of this type of plate is much less expensive and is stronger, and, because these plates consist mainly of refractory, they also can operate in very high temperatures. In this design, very often a fiberglass channel is installed around the outside edge (Fig. 17), which serves both to reinforce and to provide an impact material to protect the outside edges of the end plate.

Stud boards, typically used to support coils and to form the enclosure around the induction coils, generally are made from electrical-grade sheet laminates and polyester electrical insulation boards. These materials are designed to be self-extinguishing, feature good impact resistance and excellent mechanical strength, are track resistant and flame retardant, and have excellent electrical insulation properties. Electrical grades commonly used for this application are GPO-2 and GPO-3. The Underwriters Laboratories' listed temperature index for this type of material is 160 °C (320 °F) for the GPO-2 and 140 °C (285 °F) for the GPO-3. There are many other glass-laminated electrical insulation boards that feature even greater mechanical strengths and even higher temperatures; these generally are known as National Electrical Manufacturers Association (NEMA) G5, a melamine glass cloth sheet, and NEMA G7, a silicone glass cloth sheet that offers perhaps the highest temperature rating of these types of materials.

Refractory Lining and Installation Practices for Induction Heating Applications

Induction forge coils generally use a refractory to protect the windings from the heat generated by the induction process as it heats the billets, bars, or slabs. The large majority of the induction coils are cast refractory. Some designs use the refractory as a grout, covering only the interior of the winding, with excess refractory pushed up and between the coil winding. Some designs use only the refractory and one complete unitized monolithic cast block that both supports and protects the coil winding. Other designs feature a combination of either aluminum frame work or structural fiberglass mat to enclose and support the coil, which then is backfilled with refractory with the entire ID cast.

Replaceable liner designs also are used where suitable. A cast ceramic tube is manufactured using a suitable refractory that sometimes incorporates nonmagnetic stainless steel needles to help hold the material together. Once this tube is dried, it is wrapped with a fibrous ceramic material, a thin layer of mica paper, and then taped and inserted into the induction forging coil. The mica paper can provide both high-temperature dielectric protection for copper coil winding as well as a slip plane to assist in the removal of the cast liners when they need to be replaced.

Refractory Use

To select the most appropriate refractory material to protect heating coils, induction heating applications generally are divided into two categories: higher-temperature forging, bar-heating, and billet-heating applications; and lower-temperature hardening/tempering applications. Most of the high-temperature applications typically range from 1100 to 1300 °C (2000 to 2350 °F), whereas most hardening and heat treating applications are below 1100 °C (2000 °F).

Fig. 17 Two billet-heating coils that feature the cast refractory end plates with fiberglass channel installed around the outside perimeter. Courtesy of Pillar Induction

Fused silica refractories are the refractory of choice for a broad range of operating temperatures. Aluminum oxide (Al_2O_3)-base refractories ranging from 55 to 99% alumina are used in applications in which resistance to higher temperatures or mechanical impact is required. The degree of scale formation should be considered as part of the refractory selection process.

Refractory Selection

Fused silica refractories normally are used due to the excellent thermal stability of the fused silica grain. This grade of material will better resist the cracking that is associated with thermal cycling. Most fused silica castables have a nominal use temperature of approximately 1200 °C (2200 °F). At temperatures above 1200 °C (2200 °F), the fused silica converts to quartzite and will not withstand thermal cycling without cracking. This results in a maximum temperature of approximately 1315 °C (2400 °F) for this material.

Alumina refractories range from mullite-base formulations (55 to 70% Al_2O_3) to tabular alumina-base (94+% Al_2O_3) products. Lower-alumina refractory materials offer good resistance to cracking associated with thermal shock and mechanical impact. Higher-alumina refractories offer excellent strength properties and resistance to scale; however, they tend to crack more readily upon repeated heating and cooling during operation.

General Refractory Installation Guidelines

Because refractory linings in induction heating applications are used to protect the cooling coil, they generally are intricate in design, with thin cross sections. This requires a fine-grained castable refractory that flows well between the coil turns and also provides a smooth finish that does not interfere with the induction heating process.

General instructions are listed subsequently for the placement and curing of typical refractory castables used in induction heating applications. The following are considered to be general guidelines only; more specific instructions are available from the refractory manufacturer.

Forms. Because refractory castables flow as liquids during installation, forms must be used to provide containment for the refractory mass. After initial curing, forms also are the mechanism used to give the refractory material its final shape. The use of steel collapsible casting forms allows the user to hold closer dimensional tolerances when used repeatedly. Wooden forms can be used for intermittent use and when it is not necessary to hold tight dimensional tolerances on larger cross sections.

Release agents allow steel or wooden forms to be removed with minimal damage to the uncured refractory material once the castable has been placed and has initially hardened. The types of release agents can range from light cooking oils to aerosol silicon sprays. Motor oils, petroleum-based products, and industrial greases should not be used because additives within refractory castables can react with petroleum-based materials and can result in delaying the castable set characteristics. Sheet products such as micanite, acetate, or polyethylene work well as a release barrier. Care should be taken to smooth out any folds or wrinkles when using sheet products, to prevent minor surface defects in the cast finish.

Mixers. Refractory castables must be mixed thoroughly before placement. A clean, well-functioning mixer is required for this step; only high-shear paddle-type mixers should be used for mixing refractory castables. Paddle mixers provide the best method for evenly distributing the water addition throughout the refractory matrix. Figures 18 and 19 show two views of a paddle-style mixer.

Rotary concrete mixers do not provide the appropriate shearing or blending action required for even water distribution. For this reason, both the mixing-by-hand- and the rotary-concrete-style mixers should be avoided.

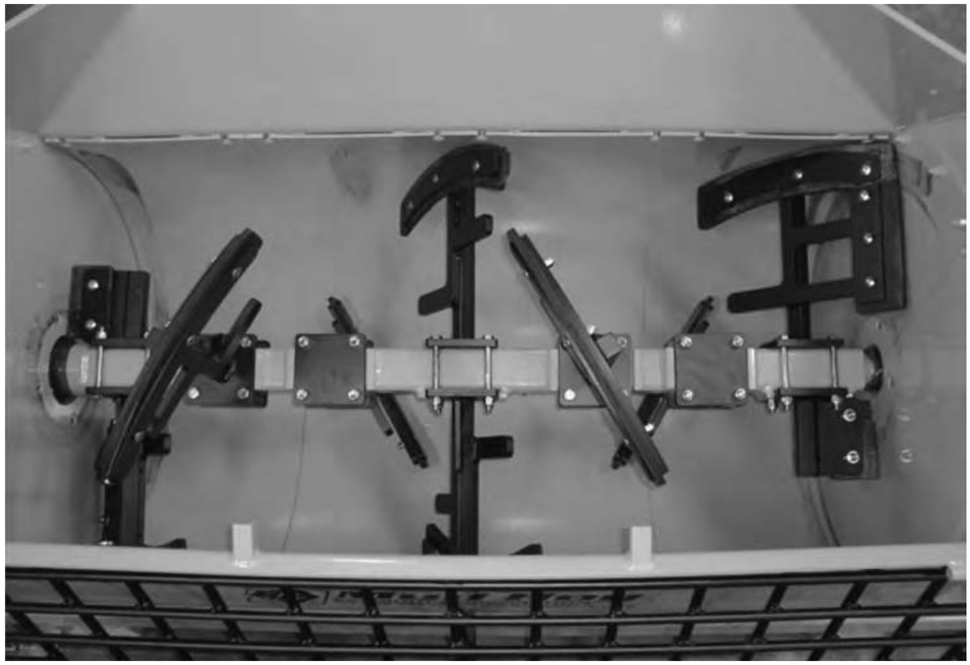

Fig. 18 Interior of a typical paddle-style mixer used to mix refractory for casting induction coils. Courtesy of Allied Mineral Products

Fig. 19 Actual paddle-style mixer. Courtesy of Allied Mineral Products

Mixing and Installation Guidelines for Castables

Refractory castables and the water used for mixing should be maintained at temperatures between 16 and 32 °C (60 and 90 °F). Casting at temperatures below 16 °C (60 °F) increases the likelihood of shrinkage cracking, lengthens set times, and slows strength development. Shortened working time typically results in temperatures in excess of 32 °C (90 °F).

It is important that potable water be used for casting purposes. A positive-displacement water meter should be used to measure the specific water requirement; normally, the required water addition can be found on the product data sheet.

Dry Mixing. Refractory castables should be dry-mixed for 30 s to redistribute any coarse aggregate that may have segregated in transit.

Wet Mixing. The water addition should be made gradually while the mixer is turning in order to evenly disperse the water throughout the refractory material. Wet mixing should take no more than 3 to 5 min; this depends on the type of refractory castable being used. Confirm the recommended mixing time with the refractory manufacturer.

After mixing, the castable should be placed using mechanical vibrators (internal or external) to densify the refractory. Care must be exercised when vibrating the material to prevent segregation or trapping of excess air into the refractory mass.

Vibration Methods

Immersible concrete vibrators are preferred for densifying large cross sections, such as refractory blocks surrounding the outside of the coil. The head should be in the range of 19 to 35 mm (¾ to 1⅜ in.), square or round. The vibrator head should be slowly immersed and allowed to densify the castable for 15 to 30 s before being slowly removed from the castable.

When vibrating thin cross sections such as the interior coil, a high-frequency vibrating table is the preferred method for densifying refractory castables. One to two minutes of vibration time typically is sufficient for thin cross sections; three to four minutes of vibration is required for larger cross sections.

When pouring refractory blocks surrounding the coil, finish the pour by screeding the castable surface. Avoid slick toweling of the surface; this can make water removal more difficult during dryout.

Curing, Form Removal, and Dryout

After placement and initial setting of the refractory castable has occurred, the form is removed and the castable should be air-cured for a minimum of 24 h prior to the application of heat. The preferable temperature range for air curing is 18 to 32 °C (65 to 90 °F).

Refractory castables must be carefully dried and heated to avoid the development of high steam pressures, which may cause explosive spalling. It is recommended that K-type thermocouples be used to monitor and control the heat-up process. Direct flame impingement must be avoided; localized heating can result in steam spalling. The use of a quality commercial bake-out oven is essential to properly dry out the refractory and eventually to bake it dry.

If the refractory material is installed within a metal encasement, weep holes should be drilled and tapped into the shell to aid in the moisture-removal process.

Drying time is dependent on the thickness of the refractory castable and ambient temperature conditions.

Note: When kiln firing (three-dimensional heating), the ramp rates must be reduced 15 °C (25 °F) per hour up to 450 °C (850 °F), and 30 °C (50 °F) per hour above this temperature. A general heatup for refractory castables is listed subsequently. Specific schedules should be reviewed with the refractory manufacturer.

General Dry-Out Schedule. This heat-up schedule, shown in Fig. 20, is for the refractory portion of the induction heating unit only. In most cases, cooling water must be circulating through the coil to protect the insulation and coating. Check with the original equipment manufacturer to confirm the maximum temperature these materials are able to withstand.

If high-pressure steam is present during the heat-up process, the heating schedule should be at that temperature until steaming subsides.

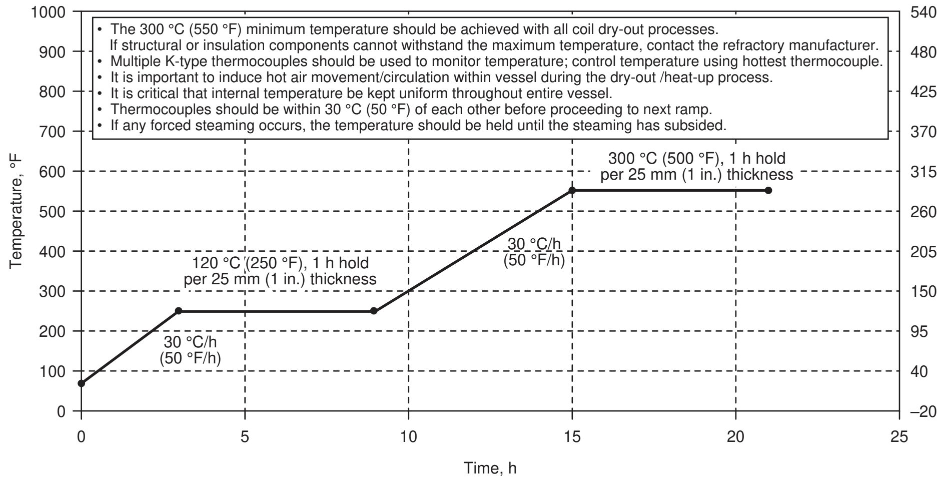

Fig. 20 General dry-out/heat-up schedule for conventional castable linings in induction heating applications. Courtesy of Allied Mineral Products

Fig. 21 Round replaceable induction coil liners used in the design and manufacture of induction coils

Fig. 22 Rectangular replaceable induction coil liners used in the design and manufacture of induction coils

Coil Liners

Replaceable coil liners, two types of which are shown in Fig. 21 and 22, are used in the design of some induction coils and can be very advantageous if designed and maintained properly. These liners generally are manufactured from a cast refractory that is blended with nonmagnetic stainless steel needles and cast into a special mold designed to break apart easily to remove the finished product. The liner then is dried out via the standard cast refractory drying process, slowly over time until it is completely dry.

Other materials, such as silicon nitrite and silicon carbide, also have been used in some limited designs. These generally have been used on smaller-diameter lower-power applications. These products generally are manufactured by companies that specialize in the manufacture of ceramics.

In most cases, the replaceable coil liners are wrapped with a layer of high-temperature thermal insulation to reduce thermal shock. This material helps to isolate the coil liner, which heats up via the thermal energy from the heated bars and billets from the cooling effect of the water-cooled coil winding. In addition to this fibrous liner material, very often a thin layer of mica is used to help provide a high-temperature, high-dielectric protective barrier to protect the coil winding from scale that may work its way through cracks in the coil liners that develop over time.

Coil Refractory Seasoning

Both new induction forging coils and induction forging coils that have been stored for long periods of time must undergo a process commonly known as coil seasoning prior to running production. Coils with refractory liners also should undergo this same process. This process involves gradually heating up a column of billets inside the coils over a long period of time until all of the remaining moisture contained in the refractory has been removed. If possible, the induction coils should be loaded with a full load of billets and heated in a static mode. If this is not possible, the speed should be set to the lowest possible level. The billets then are heated up gradually to a temperature of 260 °C (500 °F) over a 1 h period of time. After this 1 h period of time, the billets are heated up gradually to 540 °C (1000 °F) over the next 1 h period of time. The billets then are heated again gradually over the next 30 min to 815 °C (1500 °F), and once again up to 1095 °C (2000 °F) over the next 30 min. Hold the billets at this temperature for the next 15 min, and begin normal machine operation once the billets are adjusted to the desired temperature and production speed. Care taken during this process will help to afford the maximum life of the induction coils.

Wear Rails for Induction Coils

Many designs of induction coils used for bars, billets, and slabs utilize some form of wear or skid rails that are used for transporting the billets through the induction coil. The wear rails are designed to prevent damage to the coil refractory and subsequent coil winding.

The most common wear rail construction consists of a connected pair of nonmagnetic stainless steel or alloy water-cooled tubes running the length of the induction coil (Fig. 23). These water-cooled tubes can be round, square, or rectangular, in a shape to suit the application. Alloy water-cooled tube rails sometimes include alloys that were specifically designed for the heat treating industry. They consist of a heat-resistant material with increased levels of manganese to help avoid hot cracking. Inconel and other specialty alloys also are used in some applications that require materials that are nonmagnetic and offer good wear resistance in high-temperature applications.

Water-cooled wear rails also can include a wear coating applied to the surface of the rail, which will provide a much longer useful life (Fig. 24). Cobalt-base alloys consisting of complex carbides in an alloy that is resistant to wear, galling, and corrosion and that retain these properties at very high temperatures generally are best used in these applications. The exceptional wear properties are due mainly to their unique inherent characteristics of the hard carbide phase dispersed in a CoCr alloy matrix. They have excellent resistance to impact, and they maintain hardness levels of 36 to 45 HRC. These desirable characteristics have made this type of coating a standard in wear-resistance applications. The fact that the rails themselves are water cooled enables the material to maintain its high hardness levels even in the hottest sections of the induction coil.

These hard-face materials generally are applied by either flame spray or plasma-transferred arc (PTA). The flame spray process is very dependent on the skills of the technician applying the coating and is a slow, tedious process. It is the most widely used process for coating induction coil wear rails and is perhaps the industry standard. The PTA process, on the other hand, is applied automatically via machine and therefore requires less labor. The PTA process generates a more refined microstructure and consequently greater hardness than other processes, such as the flame spray and metal inert gas processes. In the PTA process, as shown in a diagram in Fig. 25 and in a photo in Fig. 26, the carrier gas is used to transport the filler material through flexible tubes to the constrictor nozzle, allowing its entrance into the plasma arc in a convergent form. The PTA process also produces a better finish, better wetting, and a wider bead area.

Hot rails, as they are referred to, are used in some applications and consist of mostly high-nickel alloys such as Inconel alloy 600 that are non-water-cooled and have 70% or higher nickel content. These alloys are nonmagnetic, nickel-base high-temperature alloys possessing an excellent combination of high-strength workability along with resistance to ordinary forms of corrosion. In these applications, there must be sufficient room for the material to grow because the hot rails will expand out of the exit end of the coil. Two typical installations of the ends of hot rails are seen in Fig. 27 and 28. They sometimes are limited in use due to this thermal expansion. Most of the materials used to manufacture hot rails begin to lose strength above 980 °C (1800 °F), and therefore, it is typical to see high wear in high-temperature applications near the end of the induction coil line. Over time, iron oxide adheres to the Inconel material and is the root cause for failures with this material. In some new alloys, aluminum oxide scaling agents have replaced the chromium oxide and are found to be more resistive to iron oxides than the chromium oxide, which has been shown to lengthen hot rail life.

Fig. 23 Coated water-cooled wear rail. Courtesy of Ajax Tocco Magnethermic

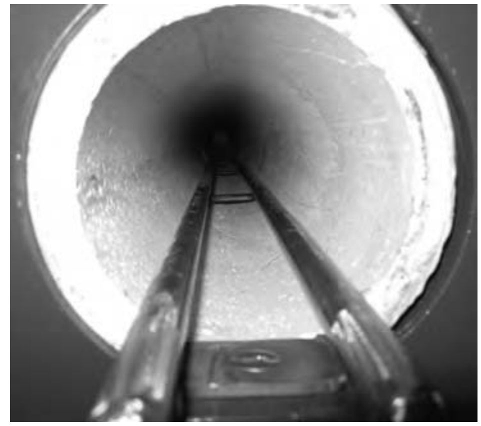

Fig. 24 Close-up view of a sample section of a plasma-transferred-arc-coated rail. Courtesy of Ajax Tocco Magnethermic

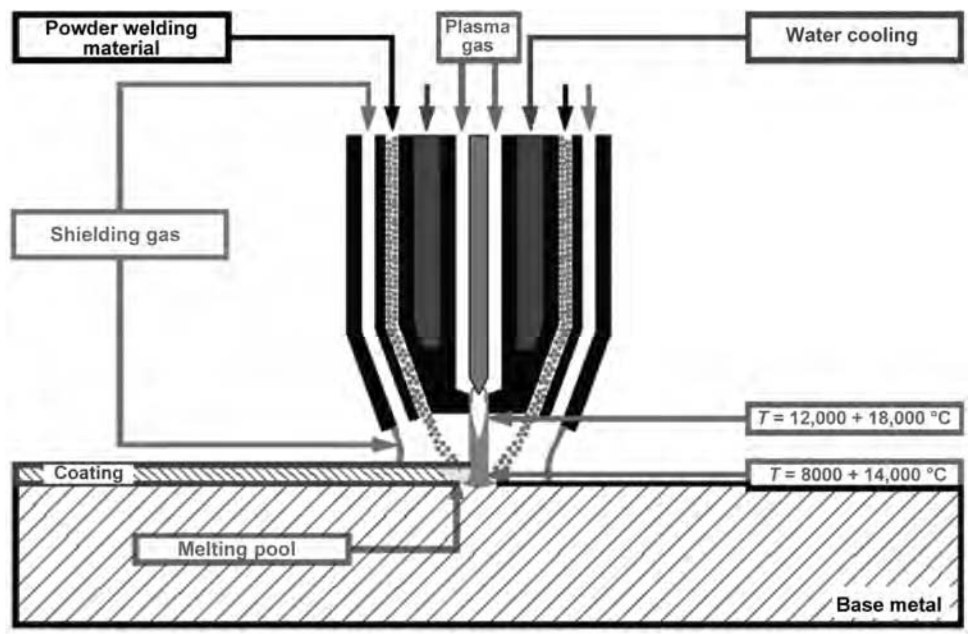

Fig. 25 Basic working principles of the plasma-transferred arc process, whereby the wear coating powder is fed into the plasma stream and fused onto the surface of the rails at extremely high temperatures and rates

Trapezoid shapes manufactured from silicon nitrite have been used for years as wear rails in limited coil designs (Fig. 29) when it is impossible to use a water-cooled rail. This material is extremely hard, wear resistant, has a low coefficient of friction, and is thermal shock resistant; however, it also breaks easily, as most ceramics do when not supported and installed properly. The trapezoid shape must be embedded into the refractory and is flush with the surface of the refractory or slightly raised approximately 1.6 mm ($^1/_{16}$ in.). The 45° angles along the edges of the shape lock it into the refractory. Care also must be taken to have sufficient refractory thickness in the areas

Fig. 26 Plasma-transferred arc process used to apply a wear bead to a rail

Fig. 27 Typical installation of the end of a hot rail installed in a round induction coil. Courtesy of Pillar Induction

Fig. 28 Typical installation of the end of a hot rail installed in a round-cornered square induction coil. Courtesy of Pillar Induction

where these ceramics are used so there is sufficient refractory under the ceramic to support the ceramic, protect the coil winding, and reduce the thermal shock that can occur when placed in close proximity to the coil winding.

Applying Power for the First Time

Care must be taken when power is applied to the coil when first used. Some manufacturers take time to carefully dry out the refractory prior to shipment. In some instances, the coil design itself will not allow the coil to be fully dried out, due to the construction material used to either enclose or support the copper coil. In coil designs that use fiber boards and other low-temperature materials, the overall coil bake-out temperature should not exceed the maximum-use temperature of the structural construction members, to prevent damage to these components. In the event that a coil is not completely dried out, it is best to load the coil with billets or bars, manually apply power, and heat the billets slowly. Slowly bring the billets up to 980 °C (1800 °F) over a 15 min period, and then maintain 980 °C (1800 °F) for another 10 min. This will allow a chemical reaction to occur in the refractory, and the moisture from this reaction will be released as steam. This is why many users report steam coming out of the coils upon initial startup. If this procedure is not followed and the coil has not been previously completely dried out, spalling typically will occur on the hot end of the coil and may damage the refractory. Cracking from this may allow scale to enter in and around the coil winding and may reduce the life of the coil itself. This same drying procedure can be used on other types of coils used for billet, bar, and slab heating, such as the pigeon hole coil, channel coil, oval coil, slot coil, and so on. These are some of the reasons that make the all-cast refractory coil one of the best designs for these applications.

Fig. 29 Induction coil designed with silicon nitrite trapezoid wear rails that are embedded into the surface of the refractory, with approximately 1.6 mm ($\frac{1}{16}$ in.) raised above the surface. The rails are used in both the entrance and exit ends as well as across the center of the induction oval-style coil in two areas where the bars are conveyed across the surface. Courtesy of Ajax Tocco Magnethermic

Preventive Maintenance for Induction Forging Coils

Preventive maintenance practices for induction forging coils may include the following:

- Ensure the refractory is cured on new or rebuilt coils, because this will improve the life significantly.
- Make sure the alignment of the coil with the materials handling is such that the parts do not come into contact with the refractory.
- Look at the shear cut on the billets and minimize any sharp edges on the billets; make sure the cuts are square. This will eliminate bridging of the billets in the coil line, especially on short billets.

- The scale that forms inside the coil should be blown out at least a couple of times per shift. Scale working its way through small cracks in the refractory eventually may cause premature coil failure.
- Inspect the refractory for cracks or fractures, and patch and seal the refractory with either the same refractory material or a compatible one. This is very important for the materials to adhere properly.
- Make sure the electrical connections are tight when installing the coil and that they are checked periodically. Loose buss connections will result in weak electrical connections and heat generated in the connection, which eventually will result in failure of the connection.
- Where the coil is bolted to the output bus, never use carbon steel fasteners. Silicon bronze or brass is the material of choice for bolting together buss and coil connections. This will ensure a good electrical connection is maintained.
- The most common cause of coil failure is water. Always maintain the proper quality, flow, and temperature of water flowing to the forging coils to prevent overheating of the coil winding, rails, and so on. Coils work best if they use the same high-quality, nonconductive, pure water that is used in the closed-loop circuits of the induction power supplies.
- If a system has flow or temperature monitors, ensure they are connected and working properly. These devices are present to prevent catastrophic failure of the induction forge coil.
- Ensure that the hose clamps are tight and that only 100% nonmagnetic hose clamps are used, to prevent induction heating of the clamp itself, which is especially important in higher-frequency applications.
- Ensure that the water connection hoses are in good repair, and replace any hoses or fittings that are damaged.
- If the coil uses water-cooled rails, periodically inspect the rails and replace them before they fail, which can result in a forge coil failure.
- Take precautions to prevent meltdowns in the coils. If the system uses lost-motion-control devices, ensure they are working properly.
- Rotation of coils, provided that all are identical, can prolong the life of the coils on systems that will allow this option. The hot end coils always are subject to the highest temperature and harshest environment. Exchanging the cold end coils with the hot end coils can result in an increase in life for the entire coil line assembly.

These preventive measures for induction coils used to heat bars, billets, and slabs apply to virtually all coil styles, regardless of the design configuration, application, or original equipment manufacturer.

Conclusion

Careful consideration must be given to the design and fabrication of induction coils for the heating of billets, bars, and slabs. A single hour of downtime due to a coil failure in a modern induction heating system can cost thousands of dollars. Cutting corners, using inferior materials, and using substandard repair and fabrication techniques simply are not options in today's (2014) competitive global market. Using the best materials and processes may cost more upfront; however, it always will pay dividends in the end by reducing downtime and all of the associated costs.

Proper maintenance programs also will prolong the life of the induction coils and will help to prevent premature failures. Following as many of the simple procedures listed previously will accomplish this task.

It is important to incorporate advances in materials and technologies into both new and existing induction coil applications, which can afford better life, less downtime, and greater system reliability.

Price alone should never be the deciding factor, because a lower price generally will cost a lot more over time. Selection of a supplier for induction systems, coil repair, and design should be a carefully thought-out process, giving a full evaluation to advanced materials, designs, experience, reputation, and ability to produce a long-lasting, reliable product designed to reduce downtime and improve efficiency of the overall system.

ASM Handbook, Volume 4C, *Induction Heating and Heat Treatment*
V. Rudnev and G.E. Totten, editors

Design and Fabrication of Inductors for Heat Treating, Brazing, and Soldering

Scott Larrabee and Andrew Bernhard, Radyne Corporation

BRAZING AND SOLDERING are bonding processes that are very similar. In both processes, assembly components are bonded together with a filler metal that has a lower melting point than the materials that make up the components to be joined together. It is commonly accepted that the temperature at which the bonding process occurs is the only factor that differentiates soldering from brazing. According to the American Welding Society, below 450 °C (842 °F) the process of using a filler metal to join two components together is soldering; above 450 °C (842 °F) the process is known as brazing. Throughout the rest of this article, the terms *soldering* and *brazing* can be used synonymously.

At the elevated temperatures associated with soldering and brazing, oxidation of the base materials will occur. The oxidation of the assembly will be more pronounced with brazing because of the higher temperatures involved. An advantage of induction brazing is that it allows for fast localized heating that minimizes the amount of oxidation that occurs during the brazing process, confining it to the heated area associated with the braze joint. Controlled-atmosphere chambers and protective atmospheres may be used with either soldering or brazing, to reduce or eliminate the need for fluxes and to eliminate oxidation.

As with induction heat treating, the success of induction brazing is highly dependent on the inductor design. Ideally, inductors used for brazing are designed to heat up the entire braze joint to a uniform process temperature. Alternatively, the inductor is designed to heat the joint area so that it is slightly hotter away from where the braze alloy is applied, to aid in pulling the braze alloy into the joint.

Inductors (commonly called induction coils or coils) that are used for brazing are similar in many ways to inductors used for induction heat treating. The general differences between inductors designed for heat treating and inductors designed for brazing and soldering are listed in Table 1.

Inductors used for brazing vary in size and shape depending on the size and shape of the braze joint area to be heated. A brazing inductor may be a simple single-turn tubular coil or an elaborate multiturn contoured coil. Figure 1 (a to k) shows various inductor configurations and geometries used for brazing. Generally, multiturn inductors made from tubing are the most common construction methods used for brazing. Figure 2 shows an example of an inside diameter heat treating coil with quench follower. This coil uses magnetic flux concentrators and has a machined profile on the current-carrying face, which is designed to precisely control the shape of the hardened area on the part to be heat treated. Brazing coils typically do not require specially machined profiles such as this, because the heated area usually does not have to be as sharply defined as in heat treating.

Materials Used for Inductor (Coil) Construction

Inductors (coils) used for brazing typically are made from annealed high-purity copper because of its high electric conductivity, high thermal conductivity, mechanical properties, and relatively low cost when compared with other metals (e.g., silver or aluminum). Using a material with high electrical conductivity/low electrical resistivity for inductors is important to minimize the resistance heating (I^2R) of the inductor. Other features of copper that make it an attractive material for fabricating inductors are that it is easily machined, very formable, anneals easily, and is readily brazed or welded to other copper or brass components. When joining two copper inductor components, such as the joints between two sizes of copper tubing, as seen in Fig. 3(a, b, and d), brazing with one of the silver braze (BAg) alloys is the preferred joining method because of its strength, durability, and ease of use. Brazing also is the preferred way for joining cover sheets to

Table 1 General differences between heat treating and brazing inductors

Property	Hardening inductors	Brazing and soldering inductors
Area heated by inductor	Heating coil face area is directly related to required hardness pattern. Well-defined heating pattern—depth and width; coil area may be smaller than area to be heat treated.	Entire braze joint area. To control cooling/heating rates of the joint area, it is often required to heat beyond the joint area.
Type of materials heated	Typically, a single material is being heated in one operation.	Coil design may need to accommodate heating of dissimilar materials in one operation. Typically, multiple types of materials are being heated.
Power density	High power density used to create well-defined heat patterns.	Lower power densities to promote temperature uniformity in braze joint area and close proximity.
Quench	Commonly use an aqueous-type quenching.	Not commonly used unless it is a gas quench/cool. Exceptions are applications requiring simultaneous brazing and hardening.
Heating methods	Single shot—entire area to be heat treated is heated at once; part may be rotated to even out heating pattern. Progressive scan heat treat—progressive heating and quenching used with elongated heat treated areas, e.g., shafts.	Braze joint area is heated in its entirety, either by single shot (generally no rotation) or while moving continuously through/past an inductor.

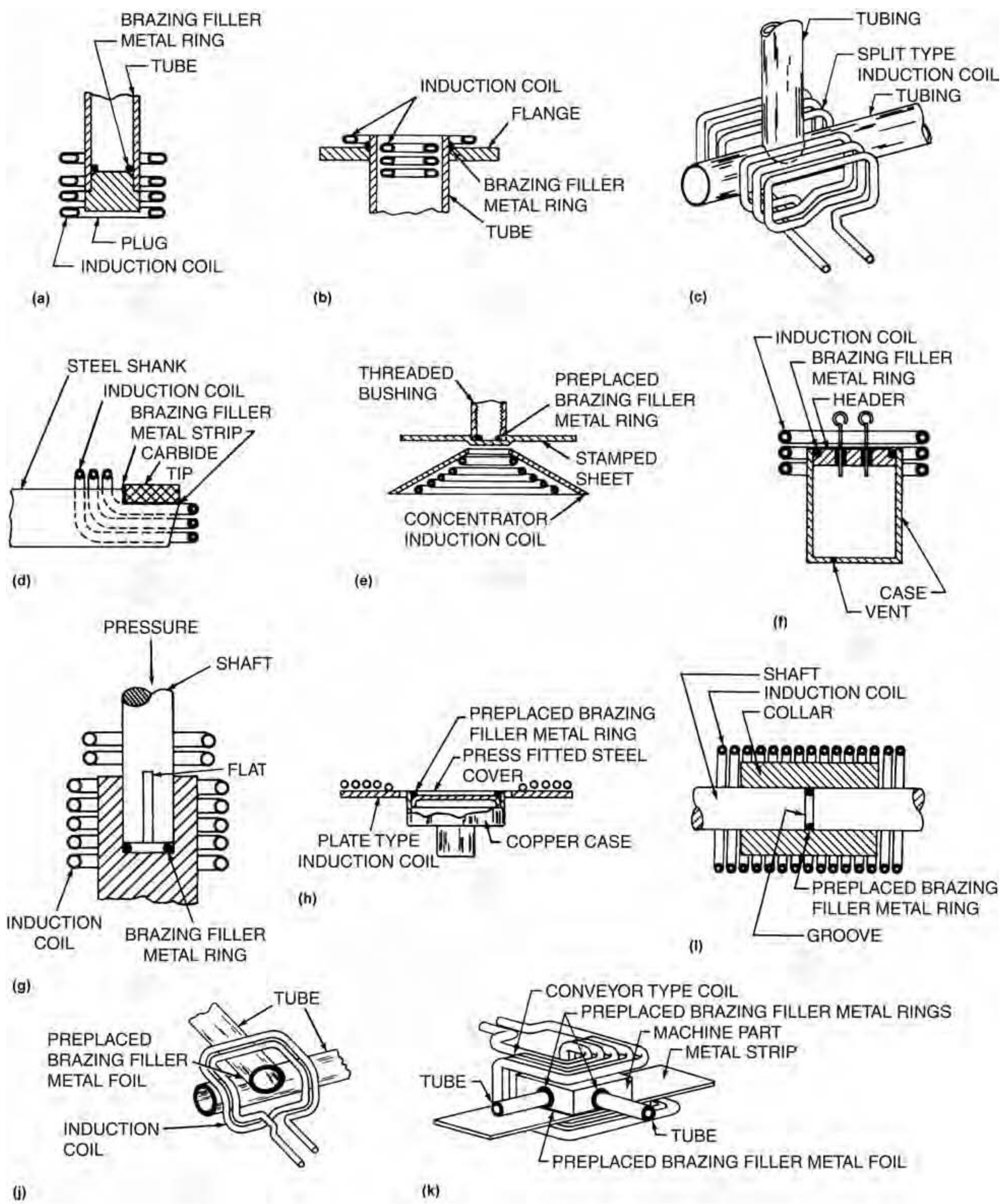

Fig. 1 Typical joint and coil designs used in induction brazing, and suggested positions for preplacement of the brazing filler-metal preforms. Courtesy of Lepel Corporation

cooling passages on machined inductors, or attaching cooling tubes to machined inductors such as those shown in Fig. 4(b to d). Figure 4 (a) shows a coil with a closed water-cooling loop created by cross drilling water paths. Plugs commonly are brazed in the ends of the cross-drilled passages. An attempt should be made to avoid placing plugs on current-carrying faces of the coil. Note that sharp corners in current-carrying areas of the coil should be avoided. Radiusing sharp corners helps to extend coil life by reducing localized current densities.

Inductor (Coil) Mounting Hardware and Peripherals. There are instances when the inductor size is such that added support is needed to prevent the deflection of the inductor caused by its own weight and/or electromotive forces generated during the electrical powering of the

Fig. 2 Example of an inside diameter heat treating coil with quench follower. Flux concentrators and a machined profile on the current-carrying face control the shape of the hardened area. Brazing coils typically do not require machined profiles, because the heated area usually does not need to be as sharply defined as in heat treating. Courtesy of Radyne Corporation, an Inductotherm Group Co.

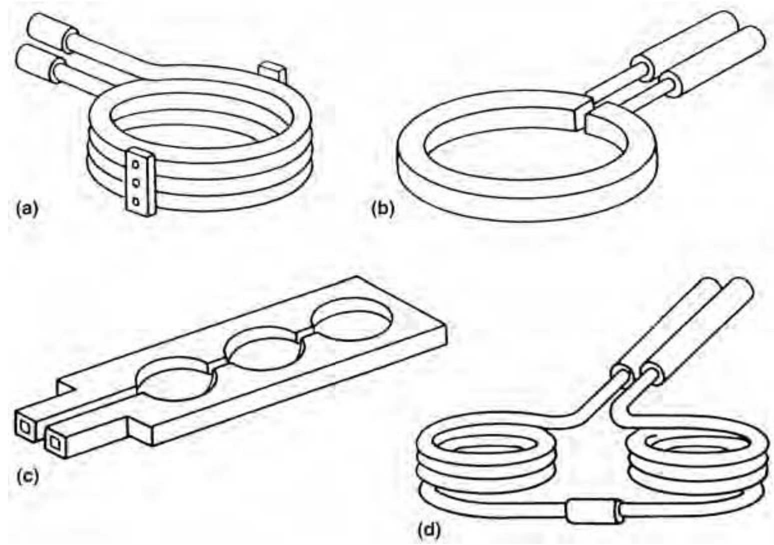

Fig. 3 Illustrations of typical inductor configurations. (a) Single-position multiturn inductor. (b) Single-position single-turn machined inductor. (c) Three-position single-turn inductor. (d) Two-position multiturn inductor. Source: Ref 1

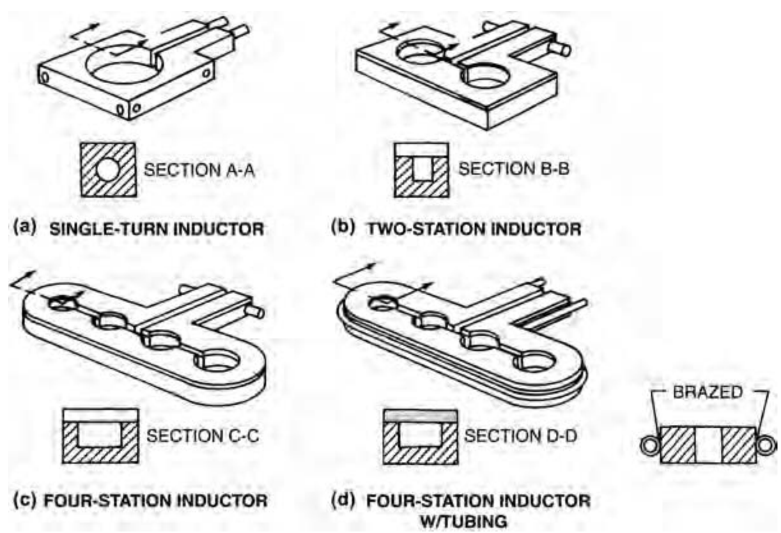

Fig. 4 Machined inductors made from solid copper bar indicating fabrication and water-cooling arrangements. (a) Single turn. (b) Two station. (c) Four station with internal cooling. (d) Four station with external cooling. Source: Ref 2

inductor. When this occurs, brass studs are brazed onto the coil and attached to polymer-based composite sheets or strips (e.g., G10) used to fabricate a support structure to help to stiffen the inductor and keep it from deflecting. Figure 3(a) illustrates how brass studs and polymer-based composite strips may be used to maintain the spacing between turns of a multiturn inductor. Brass hardware commonly is used for mechanically fastening brass support studs to polymer-based composite support structure.

All materials used in close proximity to the inductor should be nonmagnetic and preferably not electrically conductive. When components such as mounting hardware and hose clamps necessitate the use of metal components because of strength or availability constraints, nonmagnetic metals such as brass, aluminum, or austenitic (300-series) stainless steel are used. Brass generally is the preferred fastener material for attaching inductors to power supplies. When brass fasteners are not available or the mechanical strength of brass is insufficient, austenitic stainless steel fasteners can be used for attaching inductors to power supplies. When stainless steel hardware such as hose clamps is used in close proximity to an induction coil, care should be taken to make sure excessive heating of the hardware does not occur due to induced currents.

When additional cooling circuits are added to an inductor to prevent overheating of the inductor, connections commonly are made with either brass connections or push-on polymer tube fittings. Either rubber hoses (no metal braid reinforcement) or plastic tubing (e.g., polypropylene tubing) are used to connect the inductor back to the water-cooling circuit used to keep the inductor and induction power supply cool.

Field Shield Materials and Magnetic Flux Concentrator Materials. Several different types of materials and approaches have been used over the years for making field shields to keep heating from occurring in areas where it is not wanted and to concentrate the magnetic flux in the areas of the part where heating is desired.

One of the oldest ways of shielding an area where heating is not wanted is to use copper plates or sheet metal to help dissipate some of the inductor power input. Figure 5(f) is an illustration of a copper shield that may be used to shield or reduce power input to the workpiece. Note that positioning of the shield too close to the inductor may result in additional power loss. Water-cooled copper tubes are brazed to the copper shield to remove the heat dissipated in the shield. Copper plates are not used very often as dissipater shields.

Copper plates also may be used as current concentrators. Figures 1(e) and (h) are illustrations of inductors where a copper plate is being used as a current concentrator. Typically, when copper plate is used as a current concentrator, the added coil turns shielded from the part are required for added inductance to get the coil to tune properly with the induction generator so that sufficient power can be achieved to perform the desired brazing application.

Generally speaking, the following classes of materials are used for controlling magnetic flux: steel laminations, soft magnetic composites, and ferrites. Selection of one of these materials over another may be influenced by such factors as cost of material, cost of machining, or frequency range and power level at which the controllers are to be used.