



FLUXTROL®

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Induction Heating and Heat Treatment

Article:

— **Magnetic Flux Controllers in Induction Heating and Melting** —



Contents

Magnetic Circuits in Induction Applications	633
Role of Magnetic Flux Controllers in Induction Systems	633
Materials for Magnetic Flux Control.....	634
<i>Highly Conductive Materials for Field Reduction.....</i>	<i>634</i>
<i>Soft Magnetic Materials for Magnetic Flux Control.....</i>	<i>634</i>
Design Guidelines for Using Magnetic Flux Controller on Induction Coils	635
Effects of Magnetic Flux Controllers on Common Coil Systems.....	635
Cooling of Magnetic Flux Controllers.....	637
Determining the Thickness of Soft Magnetic Material	639
Magnetic Flux Control in Induction Melting Systems	639
<i>Channel Types Furnaces.....</i>	<i>639</i>
<i>Crucible Type Furnaces</i>	<i>639</i>
<i>Cold-Crucible Melting Furnaces</i>	<i>640</i>
Magnetic Flux Control in Mass-Heating Applications.....	641
Whole-Body Mass Heating	641
Local Area Mass Heating	641
Magnetic Flux Control in Induction Tube-Welding Applications.....	642
<i>Magnetic Flux Controllers for Continuous Induction Tube Welding</i>	<i>642</i>
<i>Magnetic Flux Controllers for Seam-Annealing Inductors.....</i>	<i>643</i>
Magnetic Flux Control in Local Heat Treating Applications.....	643
<i>Single-Shot Heat Treating</i>	<i>644</i>
<i>Induction Scan Heat Treatment.....</i>	<i>644</i>

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.

Magnetic Flux Controllers in Induction Heating and Melting

Robert Goldstein, Fluxtrol, Inc.

MAGNETIC FLUX CONTROLLERS are materials other than the copper coil that are used in induction systems to alter the flow of the magnetic field. Magnetic flux controllers used in power supplying components are not considered in this article.

Magnetic flux controllers have been in existence since the development of the induction technique. Michael Faraday used two coils of wire wrapped around an iron core in his experiments that led to Faraday's law of electromagnetic induction, which states that the electromotive force (emf) induced in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit. After the development of the induction principle, magnetic flux controllers, in the form of stacks of laminated steel, found widespread use in the development of transformers for more efficient transmission of energy (Ref 1, 2).

Magnetic cores gained widespread use in the transformer industry because they increased the amount of magnetic flux produced with the same alternating current. The higher the magnetic flux, the higher the emf, which results in an increase in energy transfer efficiency from the primary winding to the secondary winding.

Similar to transformers, magnetic cores were used on early furnaces for induction melting (Ref 1, 2). The benefits of magnetic flux controllers vary depending on the application. For induction heating, magnetic flux controllers can provide favorable and unfavorable paths for magnetic flux to flow, resulting in increased heating in desired areas and reduced heating in undesirable areas, respectively. Magnetic flux controllers are not used in every induction heating application, but their use has increased (Ref 3, 4).

Magnetic Circuits in Induction Applications

Induction heating applications are similar to transformers with a short circuited secondary winding. The primary winding of the circuit is the induction coil and the secondary is the

workpiece. For both cases, there are three closed loops: flow of current in the coil, flow of magnetic flux, and flow of current in the workpiece.

In most cases, the difference between induction heating applications and transformers is that the magnetic circuit is open. The magnetic field path includes not only the area with the controller, but also the workpiece surface layer and the air between the surface and controller, which cannot be changed. Therefore, the reluctance of the magnetic path only partially depends on the magnetic permeability of the controller (Ref 3). Reluctance is a term used in magnetics analogous to resistance in electricity.

Figure 1 shows a diagram of the magnetic circuit for a single-turn induction coil with a magnetic flux concentrator heating a cylindrical workpiece from the outside. The magnetic flux in the system is equal to the ampere turns of the coil divided by the reluctance of the magnetic circuit. The reluctance of the magnetic circuit consists of three basic components: the back path for magnetic flux, the coupling gap, and the workpiece. When a magnetic flux concentrator

is applied, it strongly reduces the reluctance of the back path for the magnetic flux (Ref 3). All induction heating systems can be described in this way.

The benefits of a magnetic flux concentrator on the electrical parameters for a given application depends on the ratio of the reluctance of the back path for magnetic flux to the overall reluctance in the system. It is also possible to break down basic system components into sub-components to determine the most economical use of magnetic flux controllers in a given application. Other benefits of magnetic flux controllers, such as shielding areas from heating, can also be understood by describing induction systems in this manner.

Role of Magnetic Flux Controllers in Induction Systems

Magnetic flux controllers are powerful tools in induction heating technology. In general, two primary reasons to use magnetic flux controllers in induction systems are to reduce and increase magnetic fields in a given region. Reducing magnetic fields is done by using either soft-magnetic materials or electrically conductive materials in a closed loop perpendicular to the flow of the magnetic flux between the coil and the desired lower field area. Soft-magnetic materials improve induction coil parameters, while highly conductive materials have a negative effect. Soft-magnetic materials are primarily used to increase magnetic fields.

The benefits of using magnetic flux controllers in an induction heating system include:

- Improvement of induction coil and process efficiency
- Improvement of coil power factor
- Reduction in coil current
- Reduction in unintended heating of machine components
- Reduction in undesired heating of areas of the workpiece

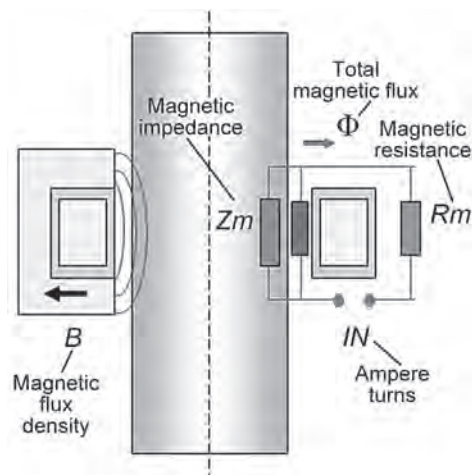


Fig. 1 Magnetic circuit in a single turn coil with magnetic flux concentrator heating cylindrical part from the outside: Φ = total. Source: Ref 3

- Precise control of the magnetic field and resulting heat pattern
- Improvement in efficiency of high-frequency power supplying circuitry
- Reduction of external magnetic fields in close proximity to the coil

In most applications, more than one of these benefits usually occurs (Ref 3–7). Recently, better understanding of the role magnetic flux controllers in induction heating systems has been obtained through comprehensive studies using computer simulation and experiments, such as those conducted at Fluxtrol, Inc. Results show that a magnetic flux controller properly used is typically beneficial in an induction heating system (Ref 3). Magnetic flux controllers play different roles in induction heating installations. Depending on the application, they are referred to as concentrators, controllers, diverters, cores, impellers, yokes, shunts, and screens. The effects of controllers in different types of induction heating applications are described here.

Materials for Magnetic Flux Control

Two main categories of materials for magnetic flux control are electrically conductive materials and magnetic materials. Electrically conductive materials typically are used in the form of shunts and screens to reduce external magnetic fields.

Two main forms of magnetic materials are hard and soft. The difference is the amount of flux density that remains after they are no longer exposed to a magnetic field. Hard magnetic materials retain a significant amount of the magnetic field, while soft materials retain almost no magnetic field when the source is turned off. Soft magnetic materials are used almost exclusively as concentrators, controllers, diverters, cores, impellers, yokes, shunts, and screens for magnetic flux control in induction systems.

Highly Conductive Materials for Field Reduction

Highly conductive materials in the form of closed loops are commonly used in induction systems to reduce the level of magnetic fields in certain areas. The effect on the distribution of the magnetic field is described by Lenz's Law, which states an induced electromotive force always produces a current whose magnetic field opposes the original change in magnetic flux. This current creates a field of reaction that influences the distribution of the magnetic field, and increases both the reluctance of the magnetic circuit and the current in the coil to produce the same amount of heat in the workpiece. These closed loops, commonly referred to as Faraday, or "robber" rings carry high frequency currents, which result in heating by Joule losses. The losses reduce the

efficiency of the system, and are not desirable. Therefore, nonmagnetic materials with high electrical conductivity are preferred for use as Faraday rings. Copper is the most common material used, but other materials, such as aluminum, are used due to cost and/or weight considerations.

Soft Magnetic Materials for Magnetic Flux Control

Soft magnetic materials most commonly used in induction systems are laminations and soft magnetic composites. Soft magnetic ferrites are used occasionally in some high-frequency applications. The main requirements are that it should have a relative magnetic permeability >1 and should not have a good electrically conductive path for strong eddy current generation.

Placing the material in the path of magnetic flux lowers the reluctance of that part of the magnetic circuit. Therefore, it requires less current to drive the magnetic flux through that part of the circuit, and a higher percentage of flux flows in the magnetic material than would flow in the same space containing only air. However, this positive effect has some limitations because the magnetic circuit is almost always open.

For the same coil current, workpiece power increases with increasing concentrator permeability very fast initially, then approaches the threshold value asymptotically. At the same time, losses in the induction coil often increase slowly with increasing concentrator permeability.

Computer simulation was used to demonstrate the diminishing positive effect of very high permeabilities in induction applications. In a real induction heating application, the magnetic permeability of a magnetic flux controller depends on magnetic flux density, frequency, and temperature of the controller itself (not the part it is heating). In the study, permeability in the magnetic flux controller is considered to be constant in the cross-section and at a fixed value for each calculation. The study was not conducted for a particular material, but is used only to show the effect of conductor permeability on induction coil parameters.

Figure 2 shows the effects of magnetic permeability on coil current and efficiency for heating a flat plate using a single leg of an inductor at frequencies of 3 and 10 kHz. Similar studies show that in most induction heating applications, the threshold value for workpiece power occurs when concentrator permeability is <100 . In high-frequency induction heating applications, the threshold value occurs at lower levels of permeability. Therefore, increasing permeability to higher values will not improve coil parameters significantly (Ref 3). In some cases, use of materials with higher than optimal magnetic permeability reduces induction coil lifetimes without any benefits (Ref 3, 8, 9).

Other important properties of soft magnetic materials, such as good saturation flux density, stable mechanical properties, low magnetic losses, chemical resistance, and resistance to elevated temperature depend on the application.

Laminations are commonly made of coated thin sheets of silicon electrical steel with 3 or 4% silicon. The laminates are cut (by water jet, laser, CNC, and electrical discharge machining) or stamped to the required shape for use in induction coils.

For induction coils, multiple laminations are stacked between mechanical supports called keepers (Fig. 3). The large lamination cross section is oriented so it is in the plane of the flow of the magnetic field; intense eddy current heating occurs if it is not in the plane.

Lamination thickness varies based on frequency used to limit eddy-current losses from the in-plane magnetic field. The lamination coating prevents an electrical connection between individual laminations. In line-frequency applications, individual laminations are typically between 0.020 to 0.040 in. (0.5 to 1 mm) thick. Laminations can be as thin as 0.002 in. in applications using higher frequencies.

Laminations have very high magnetic permeability and saturation flux density. They also have high temperature resistance limited primarily by the coating. The primary drawbacks of laminations are intense heating in 3-D magnetic fields and limited frequency range (up to about 30 kHz).

Soft Magnetic Composites consist of a soft-magnetic component (typically iron and iron-base alloy powder metal) and a dielectric component (usually an organic polymer binder). The soft-magnetic component provides a favorable path in which the magnetic field can flow. The dielectric component electrically insulates magnetic particles from each other to limit eddy current losses.

Two main forms of soft-magnetic composites are machinable and formable. Machinable materials are commonly produced via powder metallurgy compaction techniques and heat treated to improve magnetic and mechanical properties. Machining soft-magnetic composites is easier than machining laminations. The composites are applied on induction coils using an adhesive and mechanical supports (Fig. 4).

Machinable-soft magnetic composites have good magnetic permeability and saturation flux density, as well as good temperature resistance, which is limited primarily by the polymer binder. Unlike laminations, soft-magnetic composites can be tailored to work in the entire range of frequencies for induction heating and melting, and perform well in 3-D magnetic fields (Ref 3–7).

Formable soft-magnetic composites are shaped around the induction-coil surfaces, held in place mechanically, and cured in an oven, which fixes their shape. Magnetic properties of formable soft magnetic composites are not as favorable as those of machinable composites, and are used in

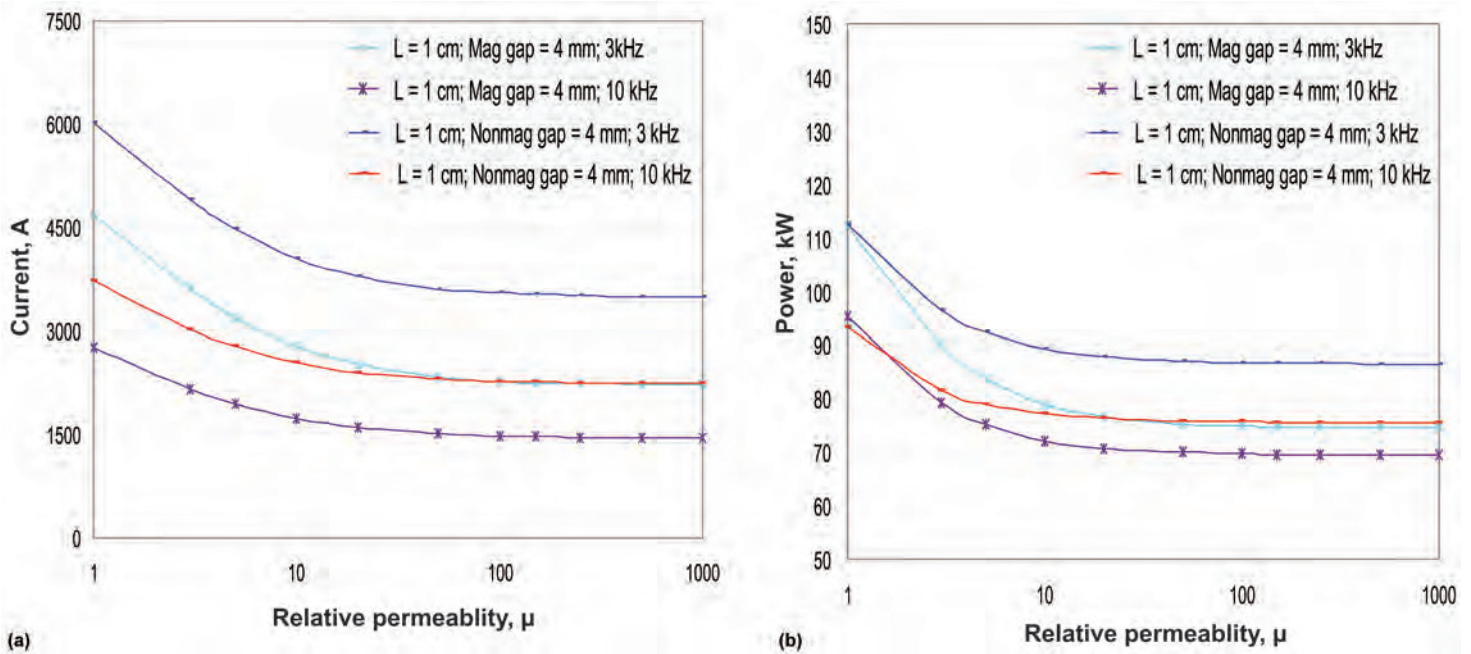


Fig. 2 Effect of magnetic permeability on coil current (a) and efficiency (b); curves generated from computer simulation of heating a flat plate using a single leg of an inductor; 50 kW in the part under the coil face. Source: Ref 3.

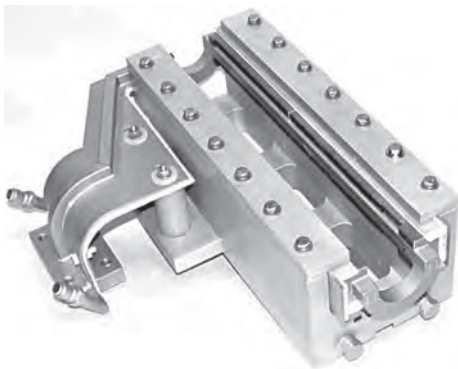


Fig. 3 Induction coil with laminations stacked between mechanical supports. Courtesy of Tucker Induction.

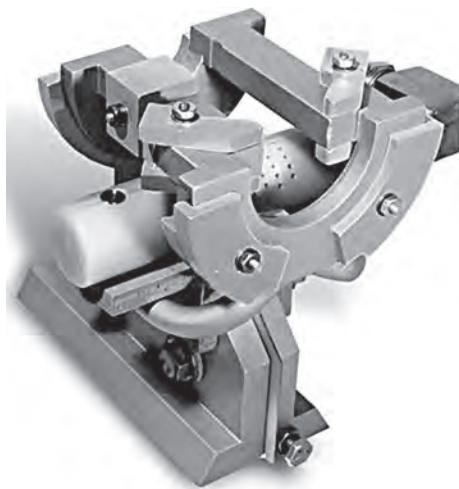


Fig. 4 Induction coil with soft magnetic composites. Source: Ref 3

instances of irregular geometries and use of a machined material is difficult.

Figure 5 shows relative magnetic permeability versus magnetic field strength of some common soft-magnetic composites (Ref 4). Their diverse properties offer the opportunity for fine control using different materials on the same induction coil.

Design Guidelines for Using Magnetic Flux Controllers on Induction Coils

The decision of where to use a magnetic flux controller depends strongly on the shape of the induction heating coil. Many induction coils are

hybrids and have components made of more than one of the basic coil types. Therefore, it is important to understand how magnetic flux flows and how it is affected by a magnetic flux controller to properly apply it on more complex induction coils.

Effects of Magnetic Flux Controllers on Common Coil Styles

Outer Diameter (OD) Coils. The basic magnetic circuit for an OD coil (Fig. 1) was described previously. Computer simulation is

used to visualize and quantify the effects of a magnetic flux controller on an induction heating system (Ref 3–7). Figure 6 shows magnetic field lines and current density in a single-turn OD coil for heating a cylindrical copper workpiece with and without the use of a magnetic flux controller. The same voltage (similar value of magnetic flux) is applied to each coil. The process was simulated using Cedrat Technologies Flux 2D software. A copper workpiece was used so current density values in the induction coil and workpiece were similar to make visualization of the effects easier.

The magnetic field is distributed in a smaller area for the coil with the magnetic flux controller, and the resulting current density in the part is concentrated under the coil heating face. Nearly all of the power induced into the part is useful, and leads to an increase in temperature in the desired heating area. Nearly all of the current in the coil with the magnetic flux controller flows on the heating face.

In the coil without a magnetic flux controller, a significant portion of the current flows in areas outside of the heating face, which does not help heating the part, but instead, draws additional power from the power supply. A significant portion of current in the coil flows up the sides of the turn and around the back; this current is not useful and only leads to additional losses in the coil, busswork, and matching components.

The reduction in current in the coil and concentration of power under the heating face is called the *concentrator effect* (Ref 3, 10, 11), and can be explained by considering the system from a magnetic circuit point of view (see Fig. 1). The concentrator effect is a result of the magnetic flux controller lowering the

reluctance of this portion of the magnetic circuit and reducing the need for current in this area of the induction coil to drive the magnetic flux around the back path.

The primary benefits of magnetic flux controllers on OD induction coils are:

- Higher efficiency
- Improved heat pattern control (ability to heat fillets, not overheat shoulders, obtain sharper transition zones, etc.)
- Better use of power in the workpiece (energy savings)

- Reduction in the induction coil current (reduced losses in power supplying circuitry)
- Reduction in heating of unintended areas of the part
- Reduction in heating of machine/structural components
- Reduction in external magnetic fields

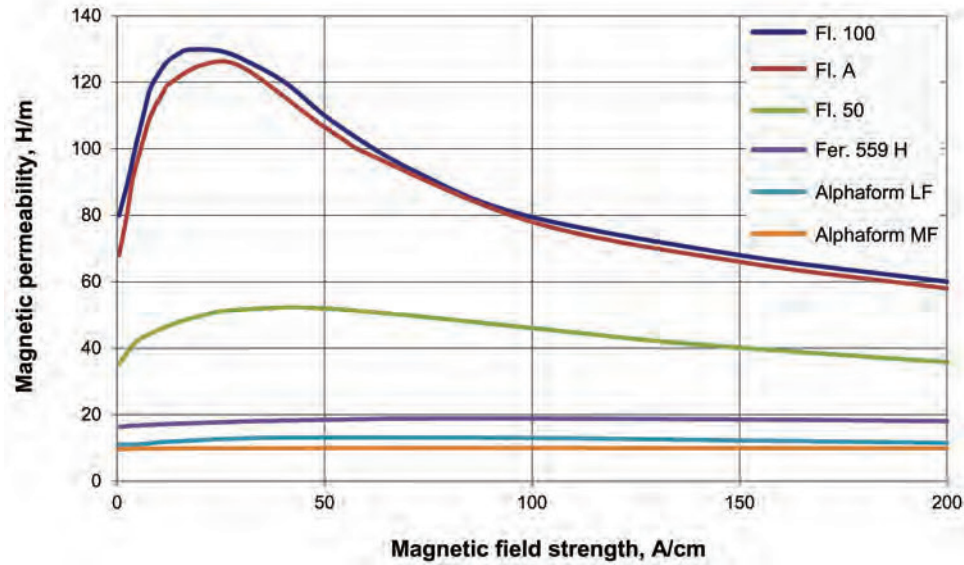


Fig. 5 Magnetic permeability of some Fluxtrol soft-magnetic composite materials as a function of magnetic field strength.

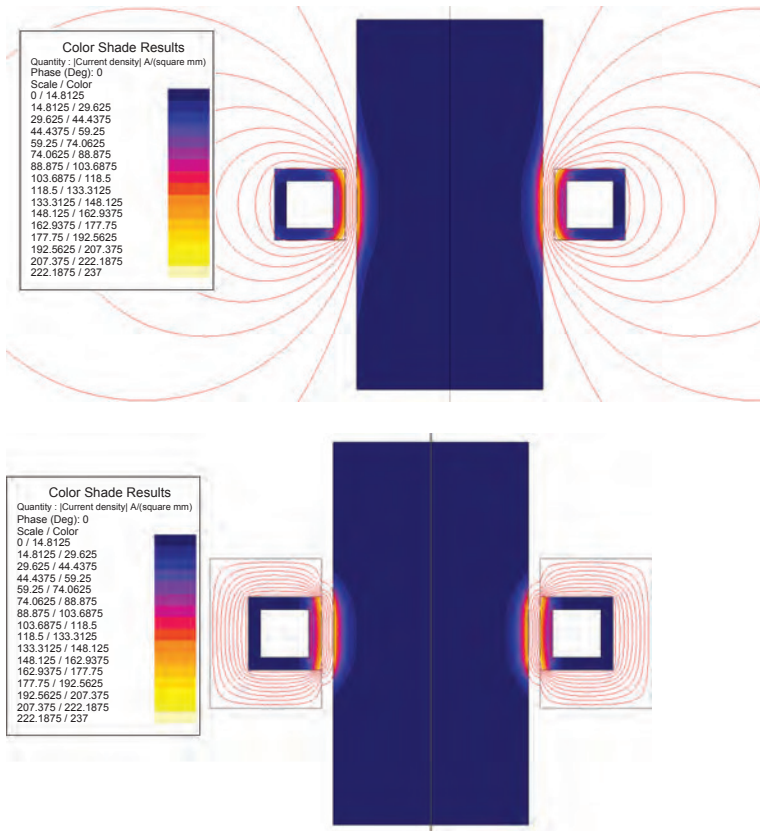


Fig. 6 Magnetic field lines and current density for a single-turn OD coil with (left) and without (right) a magnetic flux controller. Courtesy of Fluxtrol, Inc.

The aspect ratio of the induction coil must be considered to determine the impact of a magnetic flux controller on an OD coil. Two key variables are the ratio of coil length to diameter, and the ratio of the coupling gap to the length of the coil. Magnetic flux controllers are most beneficial when the length-to-diameter ratio and coupling gap-to-length ratio are small. The effects of the magnetic flux controller are reduced as these ratios increase. For very large coupling gaps relative to coil length, a magnetic flux controller can result in lower electrical efficiency.

Inner Diameter (ID) Coils. The basic magnetic circuit for an ID coil is shown in Fig. 7. The return path for magnetic flux is on the inside of the coil. Power density in the workpiece is proportional to the magnetic flux density squared, and flux density is magnetic flux divided by the cross-sectional area through which it is flowing. The magnetic impedance of an area is directly proportional to the length of the region and inversely proportional to the cross-sectional area. Therefore, the magnetic resistance (R_m) component is a higher percentage of the total reluctance on an ID coil than it is on an OD coil.

Due to the larger influence of R_m , the effect of a magnetic flux controller on ID coils is much larger than on OD coils (Ref 3, 12). Benefits of magnetic flux controllers on ID induction coils include:

- Improved coil efficiency (energy savings)
- Better use of power in the workpiece (energy savings)
- Reduction in induction-coil current (reduced losses in power supplying circuitry, coil leads)
- Reduction in heating of unintended areas of the part
- Improved heat pattern control

Magnetic flux controllers significantly improve nearly all ID coils. To determine the impact

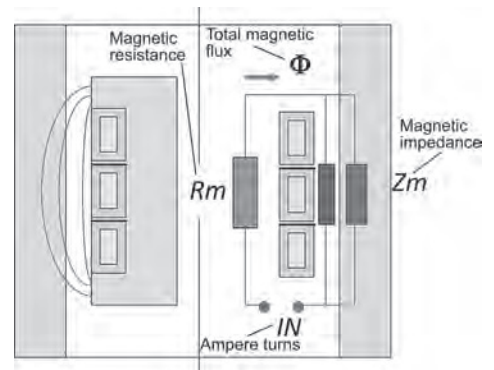


Fig. 7 Magnetic circuit for ID coil. Source: Ref 3

on the coil, it is necessary to consider the coil aspect ratio. Similar to OD coils, two key variables are the coil length-to-diameter ratio and the coupling gap-coil length ratio. Unlike OD coils, aspect ratios that benefit most from a magnetic controller are inverted. Magnetic flux controllers provide the greatest benefit when the two ratios are larger.

Linear Coils. Three basic classes of linear induction coils are:

- Coils with return current on the opposite side of the part (e.g., single-shot coils, oval coils, channel coils)
- Coils with one primary heating leg and distributed return on the same side of the part (vertical loop, split-n-return coils)
- Coils with two active heating directions and return on the same side of the part (hairpin)

The difference between linear induction coils and cylindrical coils is there is no natural flux concentrating/de-concentrating effect from the change in radius in linear coils. Therefore, the only other electromagnetic effects present are the proximity effect between coil and work-piece and the proximity effect between the coil turns themselves in the case where the return is on the same side of the part.

A hairpin inductor (magnetic circuit shown in Fig. 8) is used to illustrate the concept of a magnetic circuit for linear coils. If the coil legs are the same size and part properties under each leg are the same, each leg produces one half of the magnetic flux in the system. Magnetic flux flows around the legs of each turn. In the region

between the two turns, magnetic flux from each turn are additive, and the all magnetic flux from the system flows through this area. At the same time, the cross-section through which the magnetic flux must flow is smaller than the areas of the back path for magnetic flux. Thus, the R_m value is high on hairpin coils, and the bulk of R_m resides in the region between the two turns (Ref 3).

This phenomenon also occurs in other types of linear inductors (e.g., vertical loop, split-n-return) where the return is on the same side of the inductor; the bulk of R_m resides in the area between the turns that are in the opposite direction. Use of a magnetic flux controller in this area is very beneficial. The benefit is greatest for aspect ratios where the distance between turns relative to the coupling gap is small. The benefit is less when the heat face is long and the return is on the opposite side of the part.

Cooling of Magnetic Flux Controllers

The service life of induction heating coils with magnetic flux controllers varies from days to years. Cooling the magnetic flux controller minimizes mechanical damage and increases service life.

Heat Sources in Magnetic Flux Controllers. All magnetic flux controllers generate and absorb heat when exposed to an alternating magnetic field. The amount of heat depends on induction system parameters, induction coil and part geometry, magnetic flux controller

material, part temperature, and the atmosphere surrounding the coil.

Highly conductive nonmagnetic materials are heated by eddy currents, radiation and conduction from the hot part, and convection from the hot environment. The main heat source is from eddy currents. Because Faraday rings use the eddy-current reaction field, the primary ways to reduce losses is to use low-resistivity materials and increase the length of the shielding face.

Soft-magnetic materials are heated by eddy currents, heat from thermal sources, hysteresis losses, and sometimes by conductive heat transfer from the copper coil. Unlike highly conductive nonmagnetic materials, shielding in soft-magnetic materials is by concentration of fields of reaction rather than by reduction of the fields. Therefore, soft-magnetic materials are segmented perpendicular to the plane of the magnetic field at a small fraction of reference depth to minimize eddy currents.

The electrical resistivities of laminations are similar to those of steels, so individual lamination thickness should be between 0.002 to 0.040 in. depending on frequency. With proper lamination thickness, eddy current losses in 2-D magnetic fields make up a small portion of the heat that needs to be removed. In 3-D magnetic fields, eddy current losses grow rapidly in laminations and are larger than the other heat sources (Ref 3).

Soft-magnetic composites typically have electrical resistivities several orders of magnitude higher than those for laminations. In general, composites that will be used in higher frequency applications should have higher electrical resistivities. Therefore, the allowable thickness of soft-magnetic composites is much larger, enabling fabrication of the concentrator from one or only a few components. Global eddy current losses in soft-magnetic composites generally make up a small fraction of the total heat (Ref 3).

For soft-magnetic composites, besides global eddy current losses, there are also eddy currents in the individual magnetic particles. Similar to eddy currents in larger bodies, losses in individual particles are controlled by particle size and composition. Smaller particles are typically used for higher frequencies. In most induction applications, eddy current losses in individual particles make up only a small portion of the total heat (Ref 3).

When the correct magnetic flux controller is used, hysteresis losses make up the largest component of heat that must be removed. Hysteresis losses are due to internal friction of magnetic domains as they reorient in the presence of an alternating magnetic field.

A hysteresis loop is used to characterize magnetic hysteresis for a given magnetic material (Fig. 9). Key points on the curve are saturation flux density, remanence, and coercive force. Saturation flux density is the threshold value for the magnetization of the material. Remanence is the magnetism that *remains* after removing

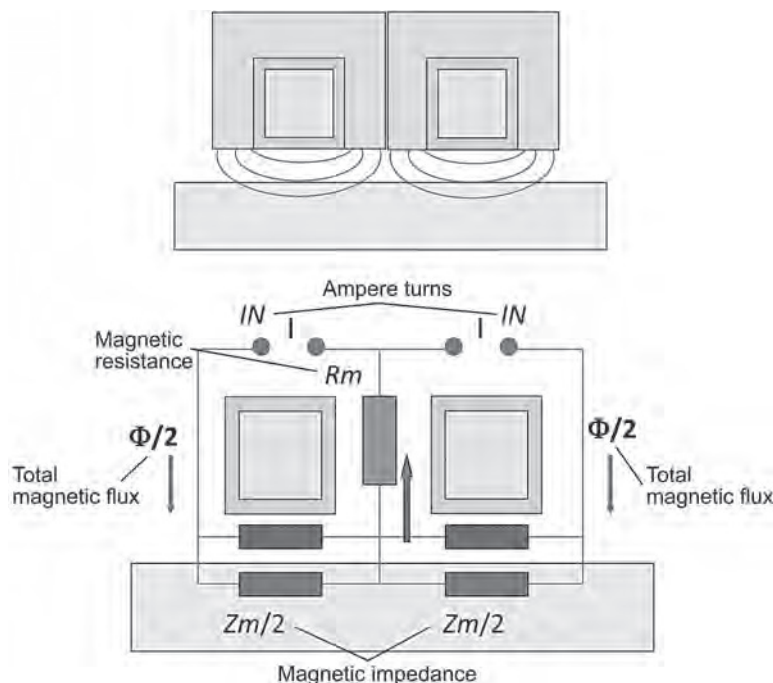


Fig. 8 Magnetic circuit for a hairpin inductor coil. Source: Ref 3.

the source of the magnetic field. Coercive force is a measure of how much magnetic field must be applied in the opposite direction to remove the remanence.

Losses in a magnetic material due to hysteresis are proportional to the product of the area of the hysteresis loop and the frequency. For good soft-magnetic materials, the hysteresis loop should be as narrow as possible. Minimizing hysteresis losses is accomplished through alloying elements and by stress relieving the material (Ref 3).

Heat Removal in Magnetic Flux Controllers. The cooling method depends on the type of magnetic flux controller used and the process environment. Power density losses in Faraday rings are higher than in soft-magnetic materials. However, removing this heat is easier due to the nature of the materials. Depending on the magnitude of eddy current losses, Faraday rings can be cooled using internal water cooling, free convection, and conduction to a large structure.

Losses in soft-magnetic materials (approximately directly proportional to frequency) are small compared with those in the copper coil, which are usually proportional to the square root of frequency. For low frequencies, the ratio between copper losses and soft magnetic losses is large. It is smaller at higher frequencies, but copper losses are still the dominant factor in total coil losses below several MHz.

For soft-magnetic materials operating at low frequencies or low power densities, cooling by free convection is sufficient to maintain a satisfactory temperature provided the atmosphere is at a temperature low enough to remove heat and the magnetic core is not continuously exposed to direct radiation from a hot part.

For medium frequencies and power densities, the most common method to remove heat is conduction to the water-cooled copper (Fig. 10). A thermally conductive adhesive is placed between the soft-magnetic material and copper tubing to facilitate heat removal. Desirable thermal conductivities of laminations and soft-magnetic composites are 15 to 100 times lower than that for copper, and the thermal conductivity of adhesives is even lower. Adhesive layer thickness, consistency of gap filling, and adhesive thermal conductivity each play a critical role in heat removal from the magnetic flux controller. The use of a 0.010-in. (0.25-mm) layer of an epoxy adhesive (1 W/mK thermal conductivity) with Fluxtrol materials is sufficient for heat removal in most cases (Ref 4). In instances of heavy loading, a supplemental water-cooling plate applied to the backside of the magnetic flux controller increases heat extraction.

Direct water cooling could be required in applications involving very heavy loading. Cooling methods include water channels in the concentrator (for soft-magnetic composite only, Fig. 11), supplemental water drizzle and quench head for quench-in-place applications. A coating on water cooling channels is recommended when using

direct water cooling of magnetic flux controllers to prevent water cooling-system contamination. Computer simulation shows that Fluxtrol 100 material can withstand continuous operation at

a magnetic flux density of 1 T, a frequency of 1 kHz, and direct exposure to radiation from a 1200 °C (2190 °F) part using direct water cooling (Fig. 12).

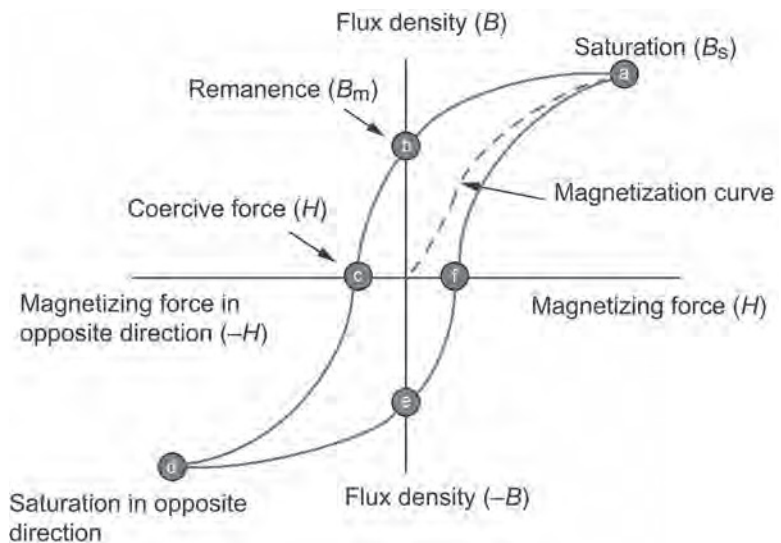


Fig. 9 Hysteresis loop for magnetic materials. Source: Ref 3

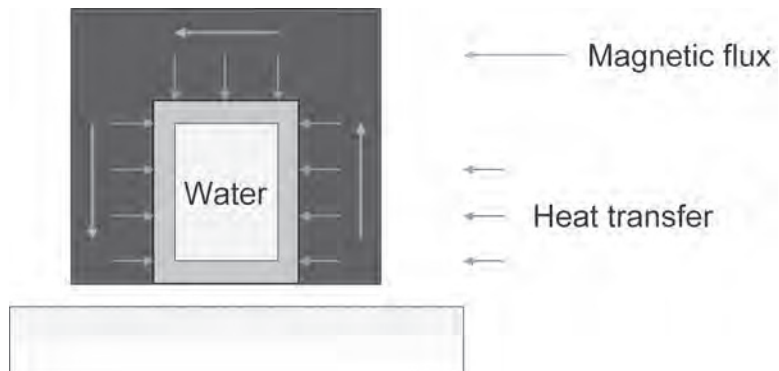


Fig. 10 The most common method to remove heat from a magnetic flux controller is by conduction to the water-cooled copper coil. Source: Ref 3



Fig. 11 Soft magnetic composite material with channels for direct water cooling. Source: Ref 4

Determining the Thickness of Soft Magnetic Material

The amount of soft-magnetic material required is determined by considering magnetic flux density, mechanical strength, and physical space available for the application. Magnetic flux density is important because both magnetic permeability and magnetic losses are dependent on it. Magnetic flux density should not exceed the saturation flux density of the magnetic controller unless there is limited available space and only partial shielding is required.

To determine magnetic loading, it is necessary to determine the magnetic flux density B in the magnetic material. For a long solenoid, it can be determined from Eq 1 if the magnitude of voltage on the coil head is known, or from Eq 2 if the magnitude of the coil current is known. In an electrical circuit, the magnetic permeability of the material is a function of magnetic flux density:

$$B = \frac{U}{\omega SN} \quad (\text{Eq 1})$$

$$B = \frac{\mu IN}{l} \quad (\text{Eq 2})$$

where B is magnetic flux density, U is coil voltage, ω is angular frequency, S is cross-sectional area, N is number of turns, μ is magnetic permeability, and l is length.

For most other coil styles, Eq 1 and 2 can provide a rough estimate of flux density. Eq 1 is better for ID coils. Computer simulation provides the best information.

Magnetic Flux Control in Induction Melting Systems

Three types of induction melting systems are channel-type, crucible-type, and cold crucible. Only the role of magnetic flux controllers in an induction melting system is discussed here. Details of each type of induction melting system are discussed elsewhere in this Volume.

Channel Type Furnaces

Channel melting furnaces are similar to either a transformer or an ID coil (Fig. 13). They should always have a magnetic flux controller or better system efficiency. Channel furnaces operate at low frequencies and are used primarily to produce large volumes of metal. For this reason, laminations are the material of choice due to lower cost and availability in large sizes.

Crucible Type Furnaces

Crucible type furnaces consist of a solenoid induction coil and a ceramic refractory or conductive (graphite or metal) crucible. Magnetic flux controllers are used on these furnaces primarily to reduce external magnetic fields, which can cause heating of the equipment structure, or can necessitate a very large footprint due to occupational safety limits for human exposure to electromagnetic fields.

Large Low-Frequency Melting Furnaces. Faraday rings and shunts are used in many large furnaces; shunts are used on the OD of the

induction coil and a combination of Faraday rings and counterwound turns are used on the top and bottom of the coil. A crucible melting furnace is shown in Fig. 14. The design is typical of low-frequency (tens to hundreds of Hertz) furnaces used to melt large volumes of metal.

Shunts used in these furnaces generally are silicon steel laminations contained in a metal support structure. Silicon-steel shunts work well on the back of the induction coil because the field is regular, in one direction, and of a simple geometry. Shunt assemblies with lamination shunts are less expensive than alternative materials such as soft-magnetic composites for large low-frequency furnaces.

Incorporating laminations on the top and bottom of the induction coil is more difficult, which is why a combination of counterwound turns and/or Faraday rings is used to reduce the level of magnetic fields in this area. These methods effectively control external fields, but reduce coil efficiency.

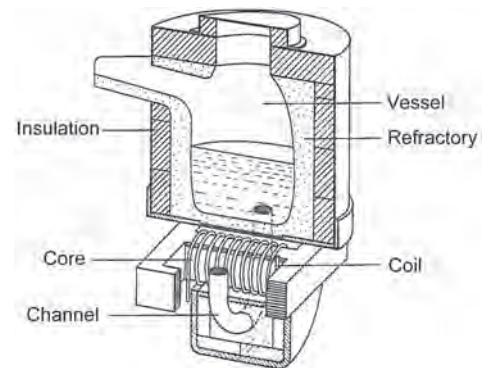


Fig. 13 Schematic of channel-type induction melting furnace. Source: Ref 13

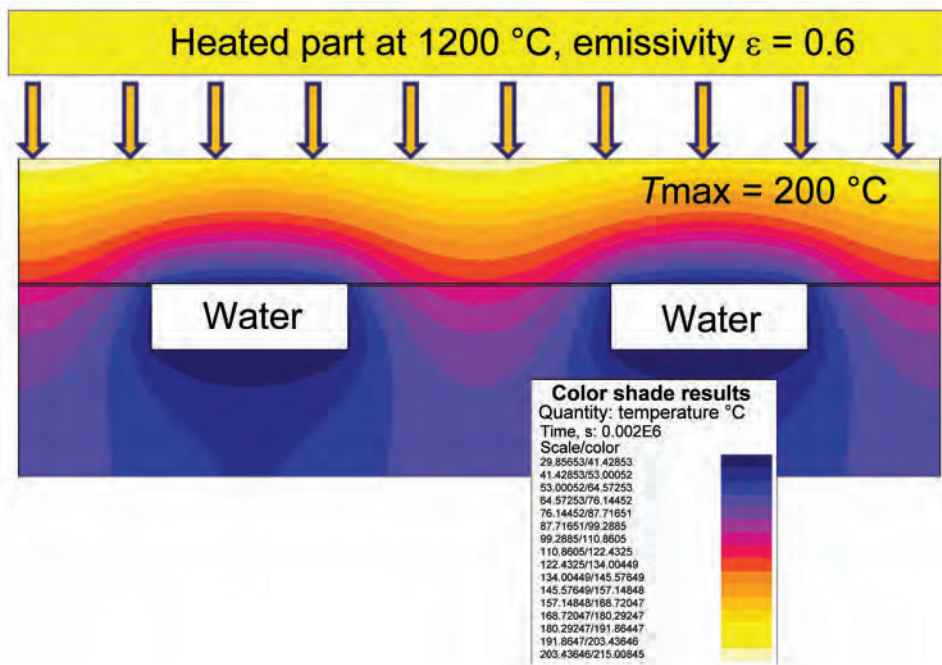


Fig. 12 Computer simulation of heat removal from soft-magnetic material exposed to a magnetic flux density of 1 T, a frequency of 1 kHz, and a 1200 °C part by direct water cooling. Source: Ref 4

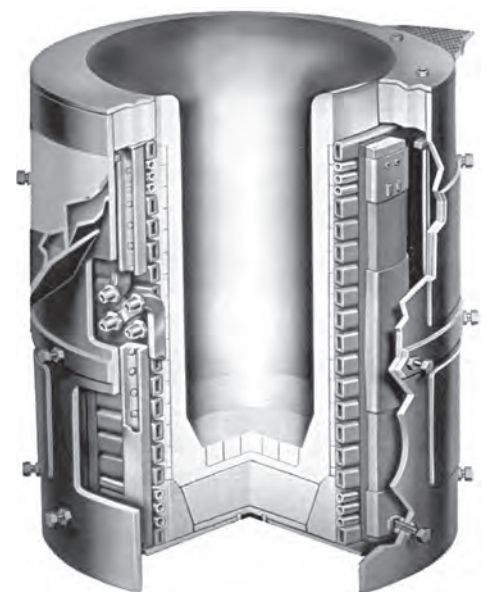


Fig. 14 Sketch of induction crucible-type (coreless) melting furnace. Source: Ref 2

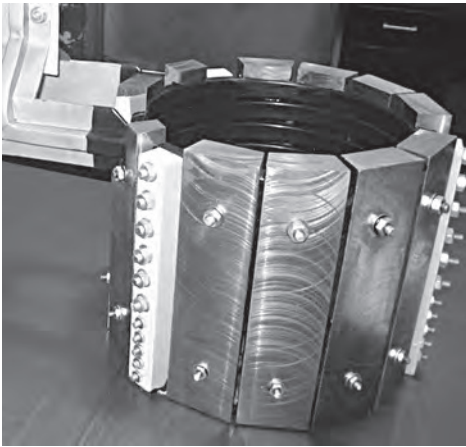


Fig. 15 Medium-sized melting coil with soft-magnetic shunts. Courtesy of Fluxtrol, Inc

An alternative method is to use a soft-magnetic composite ring on the top of the induction coil backed by a Faraday ring. The composite strongly reduces the level of magnetic field to which the Faraday ring is exposed with lower losses than using counterwound turns. Losses of this type of assembly are much lower while providing the same level of shielding. A drawback of this approach is higher initial cost. Capital versus operating costs should be considered when choosing between top and bottom shielding.

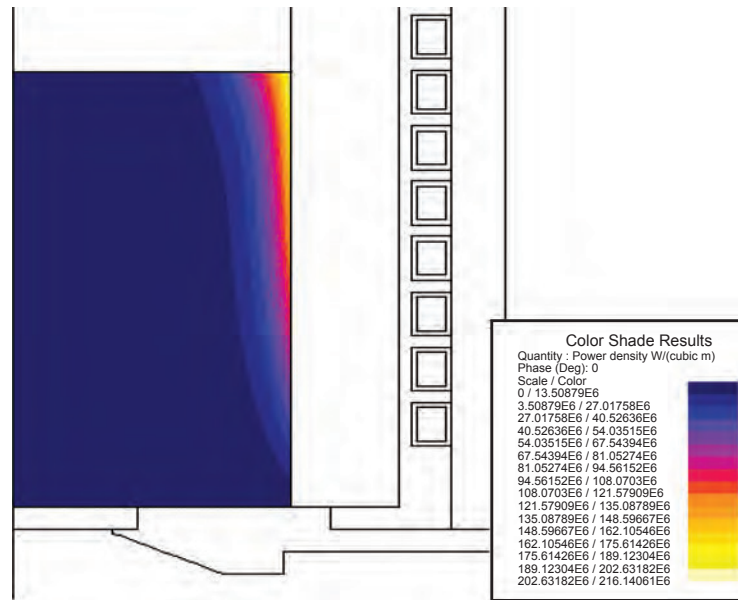
Medium-Size Medium-Frequency Melting Furnaces. Magnetic flux controllers are used for the same purposes on 1 to 10-kHz frequency medium-size furnaces as for larger ones, but different materials are used. Many of these furnaces operate in a controlled atmosphere, where magnetic flux controllers are more important than in open air furnaces. The controllers could be used to shield the chamber from heating. Furnace size must be larger without the use of magnetic flux controllers, increasing the capital cost of the installation.

Lamination thickness decreases with increasing frequency making them more difficult to work with. Also, shunt pack structural materials heat up more at higher frequencies, resulting in an increased cost of using laminate shunt packs.

Due to these factors, the use of soft-magnetic composites is becoming more popular for medium-size melting furnaces. Figure 15 shows a medium-size melting coil with a Fluxtrol 100 soft-magnetic composite. This makes it possible to incorporate magnetic poles on the top and bottom of the induction coil, so it is not necessary to counterwind the upper and lower turns or use a Faraday ring. Therefore, the entire length of the induction coil works together to create the internal magnetic field.

Another benefit of magnetic flux controllers in these furnaces is when multiple melting *pots* are placed in close proximity to each other. The furnaces can be controlled using either one power supply or multiple power supplies. However, the magnetic fields of different pots interact if they are placed too close to one another.

Traditional design
 $PD_{\max} = 216 \text{ MW/m}^3$



Modified design
 $PD_{\max} = 279 \text{ MW/m}^3$

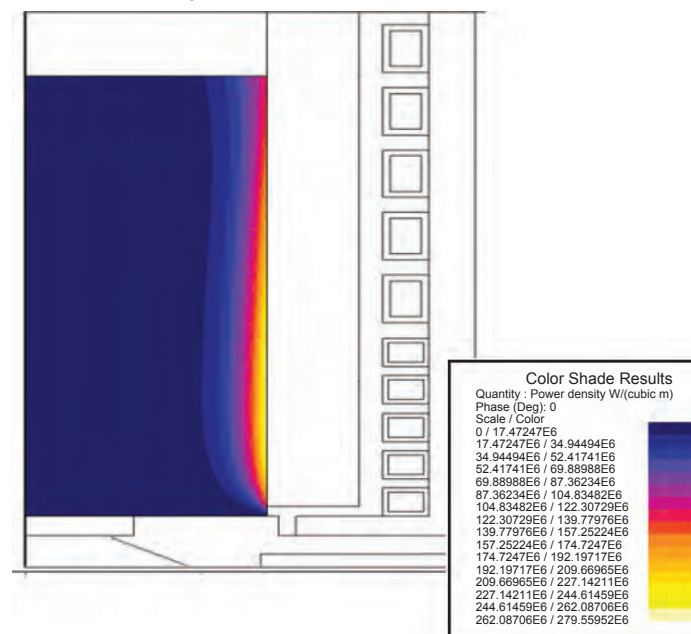


Fig. 16 Comparison of power density in the melt charge derived from a 2-D simulation using Flux 2D software: (a) traditional induction coil design with laminate shunts, and (b) modified design with a soft-magnetic composite controller with top and bottom shunts. Source: Ref 14

This phenomenon is called *cross-talking*, and it can cause nonuniform melting pot performance. Magnetic flux controllers greatly reduce the amount of cross-talking.

Cold-Crucible Melting Furnaces

In cold-crucible furnaces, a water-cooled segmented copper ring is placed between the

induction coil and the melt. Magnetic flux flows through the slots of the cold crucible and heats the melt. Water-cooled Faraday rings are often used on the bottom of the furnace. A metal *skull* typically forms between the melt and the copper components, which creates a barrier that prevents contamination of the melt by impurities.

These furnaces are less efficient than coreless melting furnaces due to electrical losses in the segmented copper ring, the lower Faraday

Fluxtrol Design

P_{total} (kW)	P_{leads}	P_{melt}	P_{coil}	P_{crucible}	$I(\text{A})$
122.5	6%	47%	15.5%	31%	1600

Traditional Coil Design

P_{total} (kW)	P_{leads}	P_{melt}	P_{coil}	P_{crucible}	$I(\text{A})$
135	6.5%	31%	21%	41.5%	1900

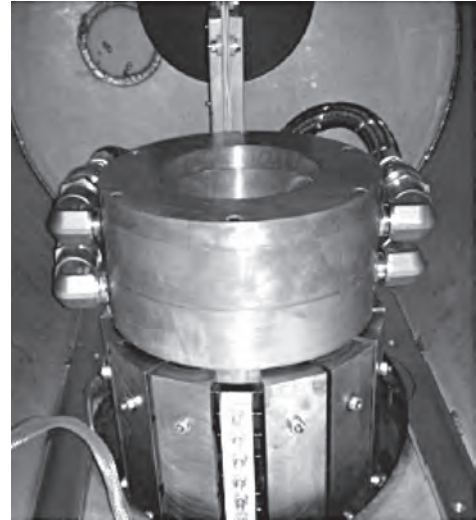


Fig. 17 Comparison of integral power values for traditional induction coil design with laminate shunts and a Fluxtrol-designed coil with soft-magnetic composite controller with top and bottom shunts. Source: Ref 14

ring, and thermal losses of the melt to the water-cooled copper components. Therefore, cold-crucible melting furnaces are typically used only in the production of metals that are highly reactive when molten or that require very low impurities. Cold-crucible processes almost always are carried out in a controlled atmosphere.

Magnetic flux controllers improve the efficiency of cold-crucible furnaces. Similar to other controlled-atmosphere melting applications, magnetic flux controllers are used on the OD of the induction coil to shield the chamber from heating.

Additional improvements are achieved by using magnetic poles on the top and bottom of the induction coil to reduce the losses associated with the Faraday rings on the top and bottom of the cold crucible. Studies show up to 50% improvement in induction coil efficiency using an induction coil with soft-magnetic composite top and bottom poles compared with a standard coil design (Fig. 16, 17) (Ref 14).

Magnetic Flux Control in Mass-Heating Applications

The role of magnetic flux controllers in an induction mass-heating system depends on the application. Of the many types of induction mass-heating installations, the largest application is heating component part prior to a shaping operation, such as forging, forming, and rolling. The role of magnetic flux controllers whole-body and local area mass-heating applications is discussed here. Detailed discussion of these types of installations are presented elsewhere in this Handbook.

Whole-Body Mass Heating

Workpieces are large in most whole-body mass-heating applications, and the part passes

through the induction coil. Part shape and induction coil length are the primary determinants of the type of magnetic flux controller used in these systems.

Long solenoids are used for long cylindrical or tubular body workpieces. Soft-magnetic controllers do not provide significant benefits for long solenoids (length = several times the diameter). Therefore, several induction coils are used to bring the billet up to the desired temperature distribution. In these installations, Faraday rings at the end of the coils are the only magnetic flux controllers used (Fig. 18). They perform two functions: shielding mechanical handling rolls from heating and preventing cross-talking among multiple coils used in the billet-heating line.

For rectangular workpieces, the benefits of a magnetic flux controller depend upon the aspect ratio of the cross-section to be heated. For square and nearly square parts, guidelines for magnetic flux controller and coil selection are similar to those for cylindrical and tubular parts. Magnetic flux controllers play a greater role for rectangular parts with one dimension significantly larger than the other (e.g., slabs, sheet, strip). In this case, both longitudinal and transverse flux heating methods are used.

Longitudinal coils generate a uniform temperature in the cross-section. Soft-magnetic materials are beneficial when the length of the induction coil is small relative to the perimeter of the coil inside cross-section.

Soft-magnetic materials should be used on transverse flux heating coils (Ref 3, 10, 15). Material selection depends on the frequency. Silicon steel laminations are used for low frequencies, and soft magnetic composites are used for middle and higher frequencies. Soft-magnetic composites are also used near the ends of low frequency transverse flux coils where 3-D magnetic fields are present.

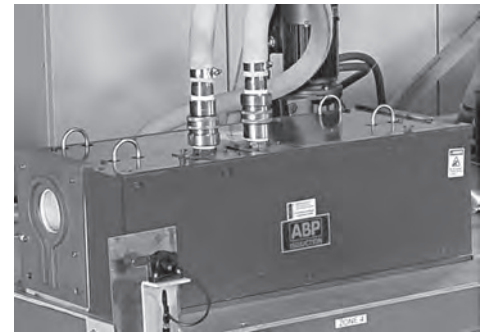


Fig. 18 Billet-heating coil with Faraday rings on both ends. Courtesy of Pillar Induction, Inc.

Local Area Mass Heating

In many cases, it is desirable to heat only a portion of the component for forming. Local area mass heating can be achieved using both static and continuous heating arrangements.

For static heating, both single-turn and multi-turn induction coils are used, where the coil I is comparable to the coil diameter. Soft-magnetic controllers applied to the induction coil improves temperature distribution and coil efficiency due to better use of power in the workpiece together with reduced coil current demand.

Continuous heating applications use a channel coil, which can be one turn to heat fasteners, for example (Fig. 19) or several turns as in a bar end heater (Fig. 20). Soft-magnetic controllers help significantly in both cases.

For single-turn channel coils, use of soft-magnetic material reduces the power required to heat the desired area of the part by 20 to 50% (Ref 3, 4). Soft-magnetic composites are the material of choice because these applications usually operate at 10 kHz or higher.

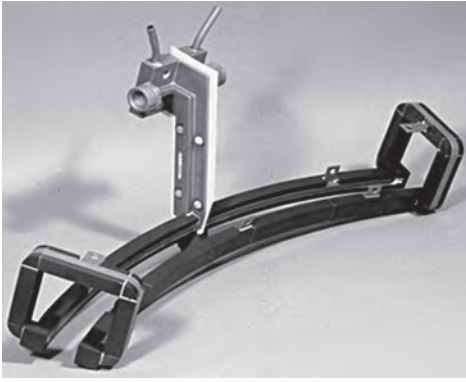


Fig. 19 Channel coil for fastener heating. Courtesy of Fluxtrol, Inc.

The effect of soft-magnetic materials on channel coils with multiple turns for heating longer sections is not as strong as for shorter single-turn coils; energy savings is typically between 5 and 20% (Ref 3, 4).

Magnetic Flux Control in Induction Tube-Welding Applications

Induction tube welding is a major application of induction heating, used in high volume production of carbon-steel tubes. It is also used to produce stainless steel, copper, and aluminum tubing. Magnetic flux controllers play a crucial role in tube-welding lines, both in the welding process and post weld heat treatment.

Magnetic Flux Controllers for Continuous Induction Tube Welding

In an induction tube welding process, steel strip is rolled into the form of a tube and passed through a cylindrical induction coil where the strip edges are heated. The strip passes through a final set of rollers that close the profile of the tube and welding occurs. Induction welding systems for steel tubing operate at high frequencies (100–500 kHz) and high power (in the range of 100 kW to a few MWs).

Figure 21 shows a schematic of current flow in the tube in a typical induction welding application. The induction coil induces a current that flows around the tube OD under the face of the induction coil. When the current reaches the open edge of the tube, it turns to close the current loop. Three options for the current to flow are:

1. Along the edges of the steel strip toward the rolls, connecting at the weld apex and returning back on the opposite edge of the tube
2. Along the edges away from the V-shape groove, returning on the tube OD of the tube farther up the line
3. Along the tube ID

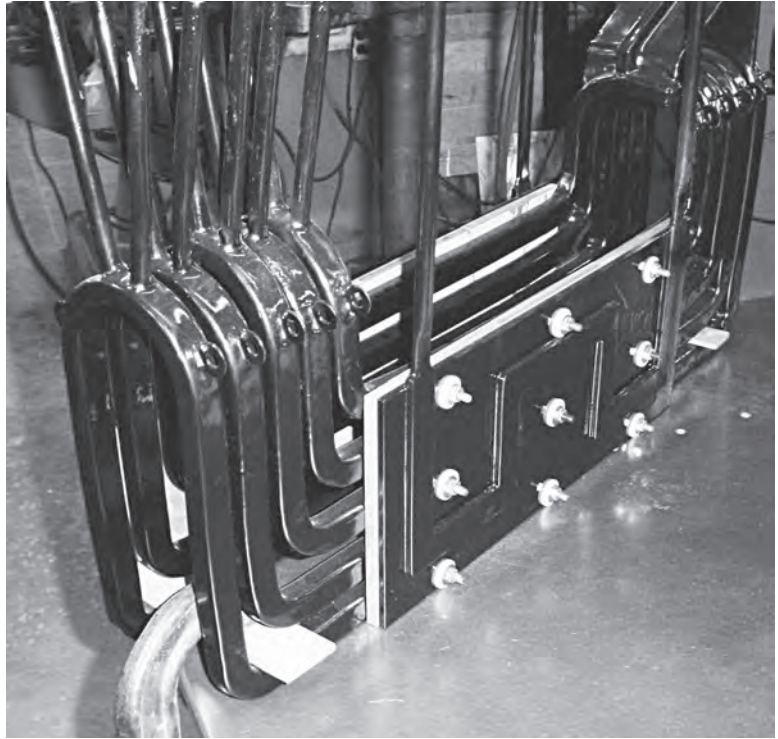


Fig. 20 Continuous bar-end heater with magnetic flux concentrator. Courtesy of Fluxtrol, Inc.

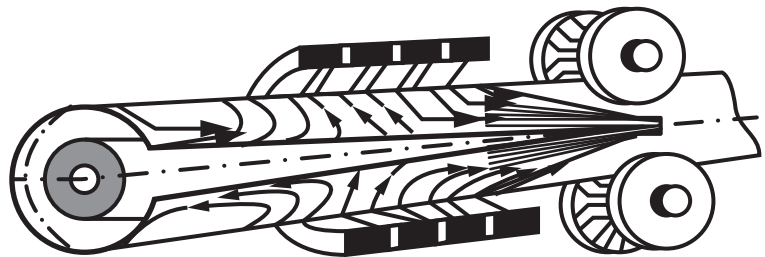


Fig. 21 Schematic of a continuous high-frequency induction longitudinal seam tube-welding system. Source: Ref 13

The first current path is the most desirable one, the second path is somewhat useful, and the third path is undesirable. In induction welding applications, a soft-magnetic material is placed inside the tube and to enhance current flow along the tube edges toward the V groove. The soft-magnetic material on the tube ID of the tube is referred to as an *impeder*, because it impedes current flow along the tube ID.

Impeders are made of soft magnetic ferrites encased in a fiberglass tube with water cooling. The tube protects the ferrite from metal spume and provides mechanical support for the brittle ferrites. The tube also keeps the ferrites in place as they often fracture in production due to thermal shock. Figure 22 shows some typical impeders used in the welding industry. For large pipe



Fig. 22 Impeders for small-tube welding; used for current flow along the tube ID. Source: Ref 16

welding systems, the impeder consists of multiple impederers assembled together, referred to as a cluster impeder (Fig. 23).

Ferrites are the material of choice in most tube-welding applications due to their low cost, high magnetic permeability at lower flux densities, and low losses at high frequencies. The drawbacks of ferrites are low-saturation magnetic flux density, sensitivity to thermal shock, and sensitivity of magnetic properties to temperature change.

The life of ferrites in the case of small tubes ranges from several hours to a week. The magnetic flux density in the impeder core is higher due to the smaller cross-section inside the tube, and ferrites become saturated. In some instances of short impeder life, ferrites have been replaced with Fluxtrol 75 soft-magnetic composite, resulting in 10 to 30% energy savings and increased life (Ref 17).

The efficiency of tube welding systems is improved using an external magnetic bridge (Ref 18). A soft-magnetic composite material placed above the tube opening helps increase current flow along the weld "V" and helps balance heating of the top and bottom edges of the tube wall (Fig. 24). In some applications, the benefits of using an external magnetic bridge are 20 to 30% energy savings and improved weld quality. System improvements from using a magnetic bridge depend on the configuration of the weld rolls. To achieve significant benefits, the magnetic bridge must be close to the weld apex without moving the coil farther away from it.



Fig. 23 Cluster impeder (multiple impederers assembled together) for large diameter pipe welding. Courtesy of Electronic Heating Equipment, Inc.

Magnetic Flux Controllers for Seam-Annealing Inductors

In some cases, the weld seam requires annealing to relieve stresses from the welding process or to improve the microstructure. To accomplish this, induction heating is commonly used, referred to as seam annealing. In instances of high production rates and for heavy-walled pipe, several seam annealers are placed in series.

Seam-annealing inductors are linear inductors, either vertical loop or split-n-return, operating at 1 or 3 kHz frequency and power levels of hundreds of kW. Figure 25 shows a typical seam-annealing induction coil in the field. C-shaped soft-magnetic materials (laminations or soft-magnetic composites) are placed over the central turn to concentrate heat on the weld seam. Magnetic flux controllers are not used on the return leg (vertical loop) or legs (split-n-return), because it is desirable to widely

distribute the return current to minimize heat generated by those turns.

Magnetic Flux Control in Local Heat Treating Applications

Surface hardening of machinery components using induction is a common application. The main advantage of induction heat treating compared with other heat treatment methods is the ability to quickly and selectively heat only the areas of the workpiece where property modification is desired. This results in lower distortion, more favorable residual stress distribution, better microstructure, significant energy savings, and the ability to place the induction system in-line with other manufacturing operations. Application of magnetic flux controllers, primarily in the form of soft-magnetic

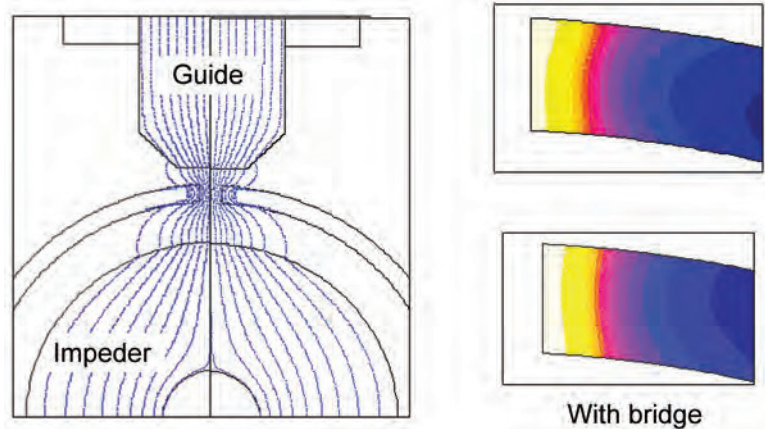


Fig. 24 Influence of a magnetic bridge on weld temperature distribution for a 40 mm OD by 2.5 mm thick tube traveling at a line velocity of 75 m/min; the bridge helps balance heating of the top and bottom edges of the tube wall. Source: Ref 4



Fig. 25 Seam annealer for tube-welding line. Courtesy of EFD Induction

materials, are particularly well suited for use in heat treating applications, because they strongly influence the power density value and its distribution along the surface of the workpiece, enabling faster heating and better heat pattern control (Ref 3–6).

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 discussion of the benefits of magnetic flux controllers in these cases follows.

Single-Shot Heat Treating

In single-shot 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 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. Common induction coil styles used for heat treating include linear coils, ID coils, encircling coils, and encircling/non encircling coils.

The most important role of soft-magnetic materials in these applications is to control the distribution of temperature and ensure good part quality. This is especially important near the ends of the induction coil to control run-out or in central areas where there are geometry changes.

Secondary benefits of soft-magnetic materials in these applications are energy savings and lower coil currents. This is especially important in applications such as simultaneous dual-frequency hardening of gears, where power levels at high

frequency tend to be large. Lower currents reduce the coil kVAs, and allow for smaller transformers and matching components, which reduce overall system cost.

Soft-magnetic materials most commonly used for induction heat treating applications are laminations and soft-magnetic composites. In some applications, a combination of laminations and soft-magnetic composites are used on the same coil. Laminations are more common on longer linear coil sections at lower heat treating frequencies (1–10 kHz). Soft-magnetic composites are more common on medium to high frequency linear coils (10 kHz and up) and coils with short linear sections. For coils with circular sections, soft-magnetic composites are more popular in most cases due to ease of application.

Induction Scan Heat Treatment

In induction scan heat treatment applications, the position of the induction coil relative to the heated length of the part does move. In many scanning applications, the part rotates during heating and quenching to ensure uniformity of pattern. Within the family of scanning applications, induction coil configurations are not as diverse as for single shot. Common induction coil styles used for scanning include encircling coils, short linear coils, and channel coils.

Encircling coils likely are the most common for induction scanning (Fig. 26). In induction scanning applications with encircling coils, the main benefit of a magnetic flux controller is in heat pattern control at the beginning and end of the part. Energy savings from the application of magnetic flux controllers is less than in the case of single-shot coils, because much of the stray heating before and after the coil is still used in the scanning process to contribute to the case depth. In some instances, such as axle scan hardening, where the heat treatment in the fillet area drives the design, magnetic flux controllers improve the pattern and achieve energy savings between 15 and 50% (Ref 4, 17, 19). Figure 27 shows some induction scan hardening coils with magnetic flux controllers used for axle scan hardening.

Linear coils commonly are used for scanning large components, such as hardening bearing races on slewing rings, and tooth-by-tooth hardening of large gears. Other applications are scan hardening of components where there is a large geometrical change. Nearly all short linear scanning coils use soft magnetic materials, because they are necessary for heat pattern control and provide large energy savings.

Channel coils are commonly used for in-line heat treatment and brazing of smaller components, such as hardening or tempering of nuts and bolts, brazing of cutting bits, and hardening of saw blade teeth. Magnetic flux controllers are used for heat pattern control and efficiency improvement. Most of these installations operate at higher frequencies, so soft-magnetic composites are the material of choice when a magnetic flux controller is used.

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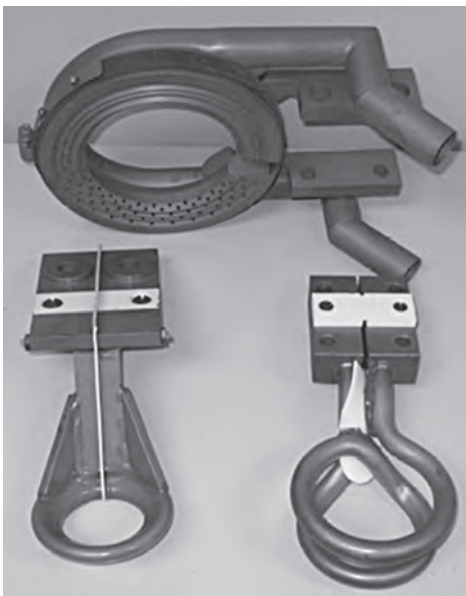


Fig. 26 Induction scan-hardening coils made of formed tubing. Source: Ref 4

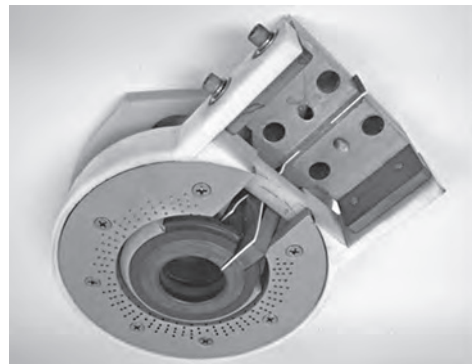


Fig. 27 Two-turn scan hardening coil with magnetic flux controllers used for axle scan hardening. Source: Ref 4



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