Magnetic Flux Concentrators

Magnetic flux concentrators (also called flux intensifiers, diverters, or controllers) are made from high-permeability, low-power-loss materials. They are routinely used in induction heat treating applications (Fig. 1) in a manner similar to that of magnetic cores in power transformers.

There are three traditional functions of flux concentrators in induction hardening: (a) providing a selective heating of certain areas of the workpiece; (b) improving the electrical efficiency of the induction coil; and (c) acting as an electromagnetic shield to prevent the undesirable heating of adjacent regions.[1] In some cases, magnetic flux concentrators are credited with turning a seemingly impossible development task into a fairly reasonable one.

This article presents basic information about magnetic flux concentrators and concentrator materials, and provides design and selection guidelines for their use in induction heat treating.

Physics of flux concentration

Without a concentrator, the magnetic flux would spread around the coil or current-carrying conductor and link with the electrically conductive surroundings (auxiliary equipment, metal supports, tools, and fixtures, for example). The concentrator forms a magnetic path to channel the coil's main magnetic flux in a well-defined area outside the coil.[1]

The current distribution in an isolated conductor is shown in Fig. 2(a). The current redistribution within this conductor when it is in close proximity to an electrically conductive workpiece is shown in Fig. 2(b). Due to the proximity effect, a significant part of the conductor's current will flow near the surface that faces the load (the "open surface" of the coil). The balance of the current will be con-

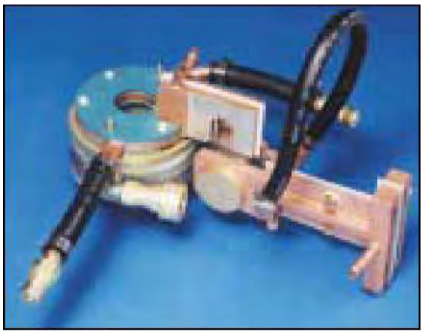

Fig. 1 — Magnetic flux concentrators for induction heating coils are made from high-permeability, low-power-loss materials. This scan inductor has flux concentrators (green rings) on top and bottom of a water-cooled single-turn copper coil. A quench ring is located below the bottom flux concentrator. Flux- trol Mfg. Inc., Auburn Hills, Mich, supplied the concentrators. Photo courtesy Inductoheat Inc., Madison Heights, Mich.

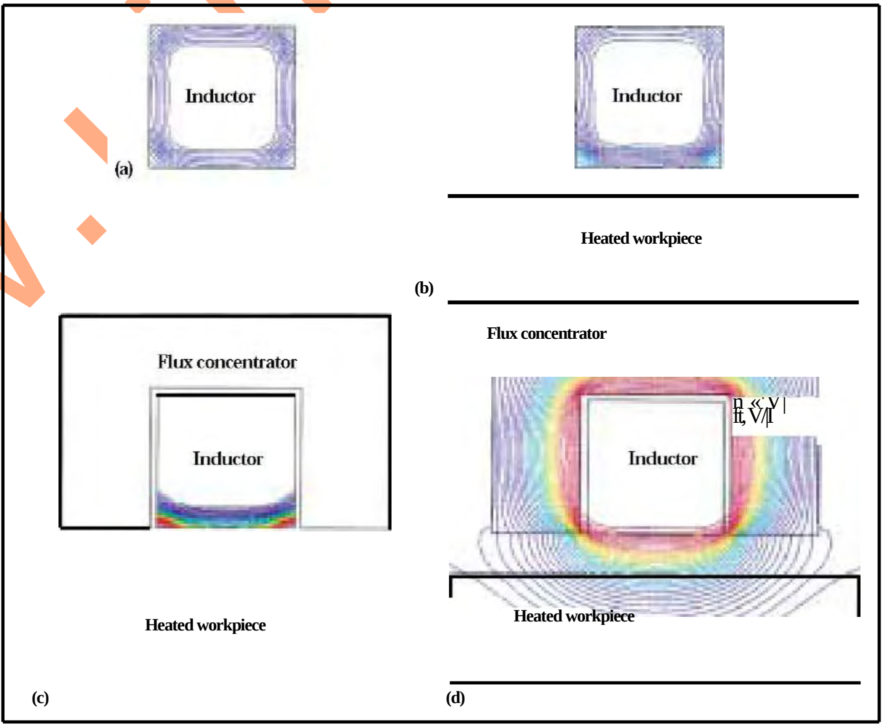

Fig. 2 — Computer modeling of coil current and magnetic field distribution. (a) Current distribution in an isolated conductor (coil). (b) Current redistribution in a conductor in close proximity to an electrically conductive workpiece. Due to the proximity effect, a significant part of the conductor's current flows near the surface that faces the load (the open surface). (c) When a magnetic flux concentrator is placed around the workpiece, practically all of the current in the coil is concentrated on the open surface (the slot effect). This improves coil-to-workpiece magnetic coupling, which results in improved coil electrical efficiency. (d) A reduction in required coil power also can be attributed to the flux concentrator's ability to localize the magnetic field.

centrated in the sides of the conductor.

When a magnetic flux concentrator is placed around the workpiece, practically all of the current in the coil will be concentrated on the open surface. The concentrator "squeezes" the current to that surface, as shown in Fig. 2(c). This is called a slot effect.[1] Concentrating the current within the surface of the coil that faces the workpiece improves coil-to-workpiece magnetic coupling, which results in improved coil electrical efficiency.

A reduction in required coil power also can be attributed to the flux concentrator's ability to localize the magnetic field, as shown in Fig. 2(d). By preventing a major portion of the field from propagating behind it, the concentrator localizes the heated area. As a result, the heated mass of metal will be smaller, which means that less power will be needed to accomplish the required heat treatment.

Will coil efficiency improve?

There is a common misconception that use of flux concentrators automatically leads to increased coil efficiency. Flux concentrators improve the efficiency of the process partly by reducing the coupling distance between the workpiece surface and the current- carrying region of the coil, and also by reducing stray losses (by reducing the reluctance of the air path).

However, because the flux concentrator is an electrically conductive body and is exposed to a high-density magnetic flux, there will be some power loss due to heat generated within it (via the Joule effect and hysteresis losses). Power loss within a concentrator could cause a reduction of coil efficiency.

The first two factors (reduced coupling distance and reduced stray losses) tend to counteract the third (power loss), and any change in coil electrical efficiency will be the sum of all three factors.

In some applications, flux concentrators will improve efficiency; in others, no improvement will be noted or efficiency may even drop. For example, there usually is no appreciable improvement in coil efficiency when concentrators are used in induction applications such as tempering, stress relieving, shrink fitting, and process annealing. The same can be said for the long solenoid-type induction coils (multiturn coils) used to heat billets, bars, and rods prior to forging, rolling, upsetting, and extrusion.

On the other hand, appreciable improvements in efficiency can be achieved when flux concentrators are applied to certain types of induction hardening coils. Examples include channel, hairpin, odd-shaped, spiral- helical, and pancake inductors; short solenoid-type coils (single-turn or mul- titurn coils); and inductors used to heat internal surfaces ("ID" coils).

Design and application features

In most cases, the application of magnetic flux concentrators does not require re-engineering of the induction system. However, when a concentrator is used, higher current densities can be generated on certain areas of the coil, Fig. 2(c). This could hasten the onset of stress cracking (by work hardening of the copper, for example) if the original coil design was susceptible to this condition. Therefore, consideration must be given to coil wall thickness, coil cooling, and the positioning of quench holes, which are frequently located near the coil surface edges. Care also should be taken at the corners of flux concentrators because of their tendency to saturate and/or overheat due to electromagnetic end effects. The initiation of stress fractures can almost always be minimized or eliminated by a well-thought-out coil design.[1]

It also is important to remember that the impedance of a straight coil can be much different than that of one having a flux concentrator. Therefore, it is necessary to check that the coil properly matches the power supply after the flux concentrator has been installed.

Special care should be taken when applying flux concentrators to multi- turn coils. With this type of inductor, the voltage across coil turns can be significant, and a short current path may develop through the concentrator. In this case, the reliability of the concentrator's electrical insulation plays an essential role in induction coil design.

Temper-back: A major problem in the induction hardening of complex- shape parts is the potential for undesirable heating of adjacent areas that already have been hardened. This "temper-back" or "annealing" is particularly important when hardening crankshafts, camshafts, gears, and other critical components.[1-3]

This is a complex problem. Due to electromagnetic field propagation, eddy currents are induced not only in the workpiece, which is located under the inductor, but in adjacent areas as well. Without a concentrator, the magnetic flux would spread around the coil and link with any electrically conductive surroundings, which would include neighboring areas of the part (cam lobes and journals, for example) and possibly areas of the induction heating machine or fixture. Induced eddy currents produce heat, which can cause undesirable metallurgical changes. Flux concentrators decouple the induction coil from adjacent electrically conductive areas, drastically reducing undesirable heating of these areas and the extent of temper-back.

Shields: Multiple coils are involved in some heat treating applications. Strong magnetic ties can form between coils because of the relatively short distances between them. This creates the potential for certain undesirable electromagnetic effects, such as power transfer between coils. In these applications, flux concentrators can be used as electromagnetic shields, drastically reducing magnetic interaction between coils.

The effectiveness of magnetic flux shields depends on such factors as frequency, magnetic field intensity, material properties, and the geometry of the induction system. Before beginning a project, mathematical modeling should be conducted to determine whether flux concentrators will be cost effective.

Selecting concentrator materials

Flux concentrator materials include laminations, pure ferrites, and proprietary iron- and ferrite-based compositions such as Fluxtrol and Ferrotron (Fluxtrol Mfg. Inc., Auburn Hills, Mich.), and Alphaform, Alphaflux, and Alphashield (Alpha 1 Induction Service Center, Columbus, Ohio).

Different applications may call for different materials. The selection decision will be based on a variety of factors. Typically, higher values of relative magnetic permeability, electrical resistivity, thermal conductivity, Curie point, saturation flux density, and ductility are sought, while lower values of hysteresis loss, Joule loss, and coercive force are desirable.[1] Additional factors in a given material's favor include the ability to be cooled and to withstand high temperatures, low thermal expansion, resistance to chemical attack by quenchants, good machinability and/or formability, ease of installation and removal, high density, structural homogeneity, low anisotropy, and low cost.

In heat treating, the materials typically used as flux concentrators are "soft magnetic" in nature; that is, they are magnetic only when an external electromagnetic field is applied. In a magnetic field, these materials can change their magnetization rapidly without much friction. They are characterized by a tall and narrow hysteresis loop of small area (Fig. 3).

Soft-magnetic materials usually have a uniform structure, low anisot- ropy, and randomly arranged magnetic domains. Random domains correspond to a minimum energy configuration — zero magnetization — when their magnetic effects cancel each other. However, the domains can be easily rearranged by applying an external magnetic field. The direction of domain rearrangement will correspond to the direction of the applied field. In this case, the material behaves as a temporary magnet.[4]

Magnetic/thermal properties: In addition to a high relative magnetic permeability and saturation flux density, magnetic flux concentrator materials also should have high values of electrical resistivity and thermal conductivity. A high electrical resistivity reduces eddy current losses, which reduces the material's temperature increase. High thermal conductivity helps extend service life by reducing the tendency to local overheating caused by heat radiation from the workpiece and/or a high-density magnetic flux.

One of the most important magnetic properties of a flux concentrator is a low value of hysteresis loss. This quality is derived from the magnetization curve (Fig. 3), which represents the magnetization process and consists of:[4]

1. A cycle of magnetization in one direction
2. A reversal of the applied magnetic field, which results in demagnetization of previously magnetized material and its magnetization in the opposite direction
3. Another reversal process resulting in magnetization in the original direction

Hysteresis loss is characterized by the conversion of electromagnetic energy into thermal energy when magnetic domains are rearranged during the hysteresis cycle, and is proportional to the area of the hysteresis loop and the frequency. (A wide opening in the magnetization curve and a high applied frequency correspond to a high hysteresis loss.)

The hysteresis loss should be as

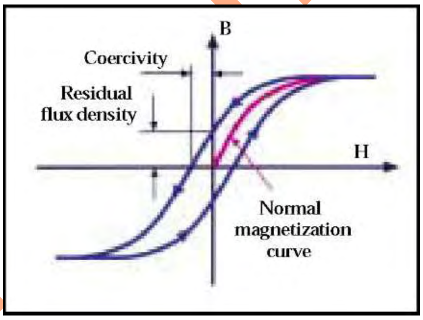

Fig. 3 — Hysteresis loop and normal magnetization curve for the soft magnetic materials typically used as flux concentrators. These materials are characterized by a tall, narrow hysteresis loop of small area. An important magnetic property is low hysteresis loss, a quality derived from the magnetization curve.

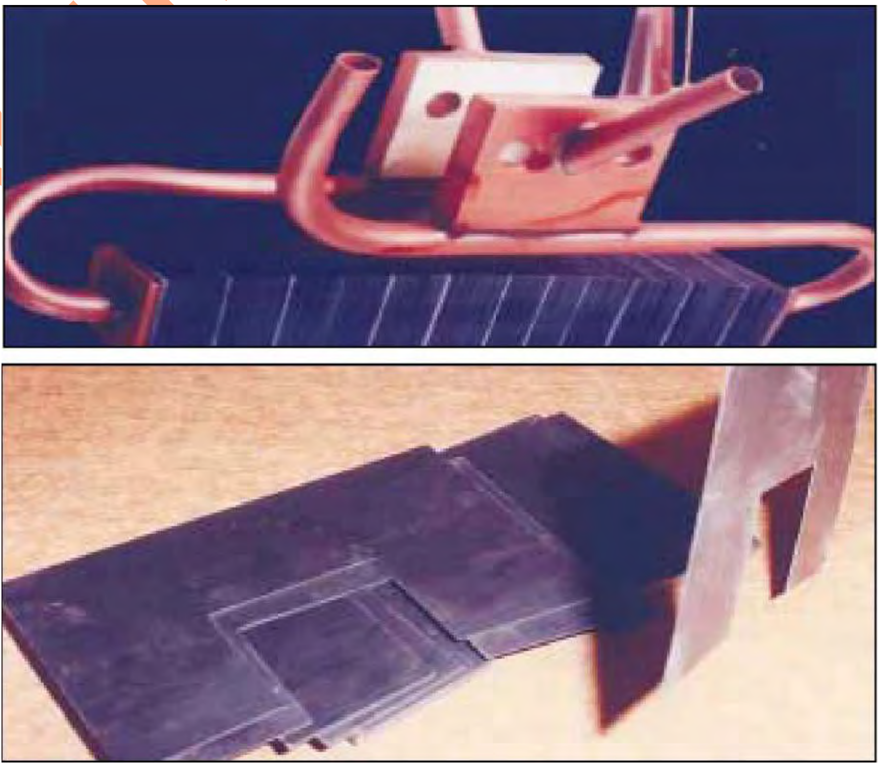

Fig. 4 — Laminations are among the materials used for flux concentrators. They are punched out of grain-oriented magnetic alloys, and stacks of them are used effectively from line frequency to 30 kHz. The typical lamination thickness range is 0.05 to 0.8 mm (0.002 to 0.03 in.).

Fig. 5 — Some flux concentrator materials are supplied in a softened condition and can easily be formed into a shape sufficiently accurate for development purposes and subsequently machined, if desired, to exact tolerances. Photos of moldable Alphaform magnetic flux concentrator courtesy Alpha 1 Induction Service Center, Columbus, Ohio.

small as possible, because its value can be correlated with a temperature rise in the flux concentrator. Too high a temperature increase can cause a loss of the concentrator's magnetism and, therefore, its rapid degradation and a reduction in coil efficiency as well as variation in the hardening pattern.

A flux concentrator material also should have a coercive force that is as small as possible. A theoretically perfect concentrator with maximum efficiency would have no magnetization remaining after the external magnetic field falls to zero.

Flux concentrator properties can be obtained from manufacturer data sheets or can be measured using the appropriate test instruments.

Types of materials: The flux concentrator materials most commonly used in induction heat treating are of these types:

1. Laminations
2. Magneto-dielectric materials, including electrolytic iron-based materials, carbonyl iron-based materials, and pure ferrites and ferrite-based materials
3. Soft, formable materials

Case for laminations: The use of laminations for induction heating flux concentrators (Fig. 4) was a spin-off from the motor and transformer industry. Laminations are punched out of grain-oriented magnetic alloys (Ni- Fe and Si-Fe alloys). Stacks of laminations are used effectively from line frequency to 30 kHz. There also have been cases where laminations were used successfully at higher frequencies (100+ kHz). Laminations must be electrically isolated from each other. Insulation is provided by mineral and organic coatings.

The thickness of individual laminations should be held to a minimum to keep eddy-current losses low. The typical thickness range is 0.05 to 0.8 mm (0.002 to 0.03 in.). Thinner laminations are used for higher frequencies, while laminations thicker than 0.5 mm (0.02 in.) typically are chosen for frequencies below 3 kHz.

Flux concentrators made of laminations are not problem-free. For example, laminations are particularly sensitive to aggressive environments such as quenchants. Rust and degradation can result. The magnetic properties of laminations can be degraded by an increase in coercive force and subsequent hysteresis loss. And if the individual laminations are not firmly clamped together, they could start to vibrate, resulting in mechanical damage, noise, and eventual failure of the coil or process. Also be alert to overheating of the flux concentrator: the corners and end-faces of laminations tend to overheat due to electromagnetic end effects. Overheating can be prevented by modifying the design of the concentrator.[1]

On the plus side, laminations are relatively inexpensive and can withstand high temperatures better than other materials. Lamination stacks also can be used to support the induction coil while being insulated from it. Another advantage is that laminations have a high relative permeability (in strong magnetic fields) and a saturation flux density (1.4 to 1.9 T) higher than that of any other flux concentrator material. This means that laminations are better able to retain their magnetic properties in the strong magnetic fields typical of most induction hardening applications.

Other choices: Pure ferrites and ferrite- and iron-based powder materials also are often used in induction hardening.[1] Ferrites are dense ceramics made by mixing iron oxide (FeO) with oxides or carbonates of one or more other metals such as nickel, zinc, or magnesium. In relatively weak magnetic fields, ferrites have very high magnetic permeabilities (p_r = 2000+). The main drawback to ferrites is their brittleness. Other disadvantages: a low saturation flux density, low Curie point (~220°C [430°F]), poor machinability, and low resistance to thermal shock.

Some flux concentrator materials are supplied in a soft, formable condition and can easily be molded into a shape sufficiently accurate for development purposes and subsequently machined, if desired, to exact tolerances. Alpha 1's Alphaform concentrator (Fig. 5) and new Alphashield magnetic shield are examples.[1] The relatively low-cost concentrators are said to be "advanced composites of insulated iron microparticles, space- age polymers, and a thermally sensitive catalyst." Although their magnetic properties are not as impressive as those of other iron- and ferrite-based concentrators, they can be economically and effectively used to reduce an external magnetic field around an induction coil.

Depending on the application, a magnetic flux concentrating "system" can be made from a single material or more than one material. For example, in a split-return coil, laminations can be located at the middle of the coil and iron- or ferrite-based powder materials placed at the coil ends. Such a design is cost-effective, electrically efficient, and increases concentrator life because it takes into account the field distortion due to the electromagnetic end effect that would result in additional losses if laminations were used at the coil ends.

Advantages/disadvantages

Magnetic flux concentrators can raise profits for the heat treater, by:[1]

- Reducing the induction coil's required power and current levels
- Improving the electrical efficiency of the process and decreasing energy consumption
- Making it possible to selectively heat specific areas of the workpiece
- Obtaining a superior hardening pattern
- Minimizing geometric distortion of the workpiece
- Preventing undesirable heating of adjacent areas
- Reducing rejects, rework, and scrap
- Lengthening equipment life
- Reducing cycle time
- Eliminating exposure of personnel to electromagnetic fields

Caveats: Of course, there is an expense associated with adding a flux concentrator to an existing inductor. A common saying among those familiar with induction heating is, "If a good part can be produced without a flux concentrator, there is no reason to add to coil cost."

Concentrators also degrade in service. As soon as they're installed, their ability to concentrate magnetic fields begins to slowly decline due to, for example, degradation of magnetic particles and rusting.

Another major concern is the reliability of the installation. Flux concentrators typically are soldered, screwed, or sometimes even glued to the induction coil. And they usually are positioned in areas of high magnetic flux density, where electromagnetic forces can be substantial.[1] Over time, these forces can cause the concentrator to loosen and unexpectedly shift or move to an improper position.

Another possible cause of concentrator loosening is unstable temperature conditions. During the processing cycle, the concentrator can be heated to 250°C (480°F), followed by cooling during quenching to ambient temperature. In typical hardening applications, this repetitive heating and cooling are accompanied by an expansion and reduction, respectively, of the volume of the concentrator, which can cause it to loosen and move. And movement of the flux concentrator can cause variations in heating and hardening patterns.

An unexpected change in the hardening pattern can be very serious. In the automotive industry, for example, this can result in the recall of many thousands of vehicles to replace the defective part. To prevent such a situation, flux concentrators should be examined on a scheduled basis and repaired if necessary. In some cases, special monitors can be installed to indicate changes in concentrator performance; however, they add substantially to total system cost.

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