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Systematic analysis of induction coil failures

PART 5: EFFECT OF FLUX CONCENTRATORS ON COIL LIFE

This multipart column presents portions of an in-depth analysis of induction coil failures. The study was initiated by Inductoheat's Aftermarket Department and was conducted over a period of several years by the company's R&D staff.

The information presented in this series will give readers an understanding of a broad spectrum of interrelated factors and phenomena that can help them identify the potential causes of a particular induction coil failure.

Parts 1–4 appeared in the August, September/October, and November/December 2005 issues, and the January/February 2006 issue.

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

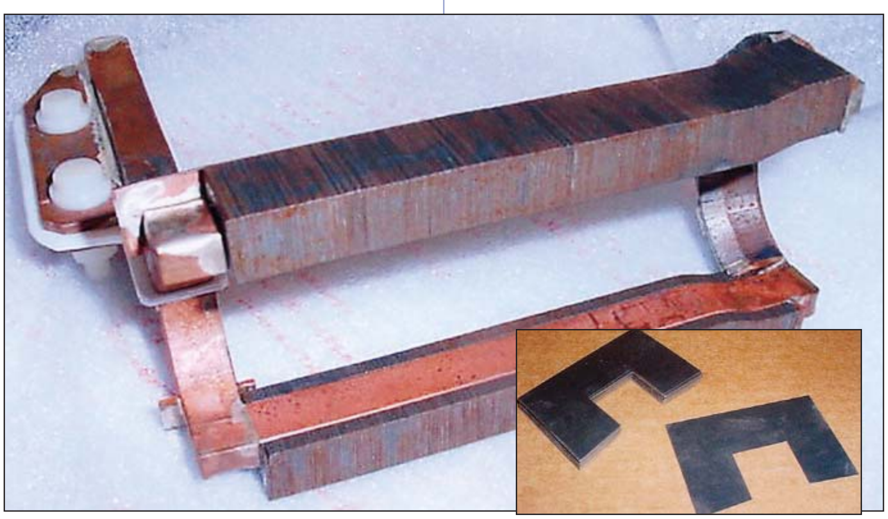

Fig. 1 — Laminations applied to a channel-type inductor function as a magnetic flux concentrator.

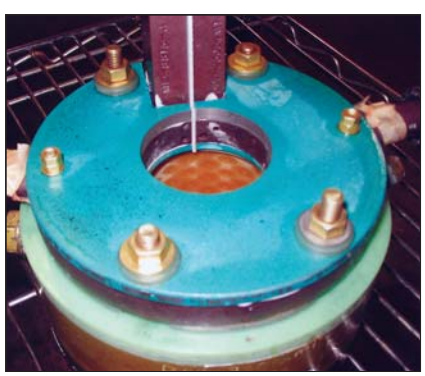

Fig. 2 — Iron-based powder flux concentrator (dark green component).

Without a concentrator, the magnetic flux could spread around the coil and link with its electrically conductive surroundings (auxiliary equipment, tools, and fixtures, for example). The concentrator forms a magnetic path to channel the coil's main magnetic flux in a well-defined area.[1–4] There are three traditional functions of magnetic flux concentrators in induction heating: (1) providing selective heating of certain areas of the workpiece; (2) improving the electrical efficiency of the induction coil; and (3) acting as an electromagnetic shield to prevent the undesirable heating of adjacent regions.[1-5]

Concentrator Materials

Different induction heating applications may call for different flux concentrator materials. Available materials include laminations (Fig. 1), pure ferrites, and materials that consist of iron-based and ferrite-based compressed powder particles (Fig. 2). Proper selection depends upon a variety of factors.[1–5] Typically, higher values of magnetic permeability, electrical resistivity, thermal conductivity, Curie point, saturation flux density, and ductility are sought, while lower values of hysteresis loss, Joule loss, coercive force, and anisotropy are desirable. A high electrical resistivity re-

Table 1 — Comparison of selected features of magnetic flux concentrators

Property or characteristic	Laminations	Iron-based or ferrite-based powder materials
Homogeneous properties	**Fair** (pronounced heterogeneous properties)	**High** (still heterogeneous)
Magnetic properties (magnetic permeability, magnetic saturation, etc.)	**High**	**Fair (**particularly in strong fields)
Curie point	**High** (about 1290°F [700°C])	**Fair** (less than 660°F [350°C])
Electrical resistivity	**High** (if installed properly in respect to the field orientation and frequency)	**High**
Thermal conductivity	**Good to fair** (depending upon orientation)	**Fair**
Maximum use temperature	**Good** (depends upon thermal insulation between sheets of laminations)	**Fair** (less than 660°F [350°C] because of low working temperature of binder)
Machinability	**Fair**	**Good**
Resistance to corrosion	**Fair**	**Good**
Typical working frequency range	50 Hz to 30 kHz	1 to 800 kHz+
Localized overheating	**Fair**	**Fair**
Ability to withstand high-temperature radiation and thermal convection	**Good**	**Fair**
Ability to be applied to complex shaped coils	**Fair**	**Good**

duces eddy current losses, which reduces the material's temperature increase. High thermal conductivity helps extend service life by reducing the probability of local overheating caused by heat radiation from the workpiece and/or a high-density magnetic flux.

Ferrite and powders: Pure ferrites and ferrite- and iron-based powder materials 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 (μ_r = 2000+). The main drawback to ferrites is their brittleness. Other disadvantages: a low saturation flux density, low Curie point (~430°F [220°C]), poor machinability, and low thermal shock resistance.

Iron-based or ferrite-based powder materials have lower magnetic permeability but better machinability. Examples of these materials include Fluxtrol and Ferrotron (Fluxtrol Inc., Auburn Hills, Mich., www.fluxtrol.com) and AlphaFlux and AlphaForm (Alpha 1 Induction Service Center, Columbus, Ohio, www.alpha1induction.com).

Laminations: The use of laminations for induction heating flux concentrators was a spin-off from the motor and transformer industry. Laminations are punched out of grain-oriented magnetic 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. Mineral and organic coatings provide insulation.

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

Table 1 compares the basic properties and characteristics of laminations and iron- or ferrite-based powder flux concentrators.

Concentrator Pros and Cons

It is important to remember that all concentrators degrade in service. Even under normal working conditions, their ability to concentrate magnetic fields begins to slowly decline as soon as they're installed, due to, for example, degradation of magnetic particles, degradation of the binder used to hold magnetic powder particles together, rusting, and other causes.

Positive effects: In some applications, but not all, the use of flux concentrators can improve coil efficiency, resulting in noticeable reductions in coil current and voltage. If copper overheating was the main coil failure mode, then a coil current reduction leads to reduced coil heat losses (Joule losses), which can appreciably lengthen coil life.

In addition, a reduction in coil current results in reduced electromagnetic forces. If coil failure was related to stress-fatigue cracking, joint water leakage, or copper banding, then lower electromagnetic forces also could increase coil life.[1,7]

If arcing was primarily responsible for coil failure, then the reduction in coil voltage due to the use of a flux concentrator can eliminate arcing and improve coil life.

Caveat: The above-mentioned factors have potential positive effects on coil life. However, a flux concentrator is an addition to the induction coil that also can adversely affect its reliability and life. No flux concentrator is completely free of potential problems.

For example, even though use of a concentrator can reduce total coil current, the localized current densities generated on certain areas of the coil can be greater than those in bare coil (see Figures 2 and 4 of Ref. 6). This could lead to localized overheating, and/or 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 geometry, coil cooling, and the positioning of quench holes in machined integrated quench (MIQ) inductors.

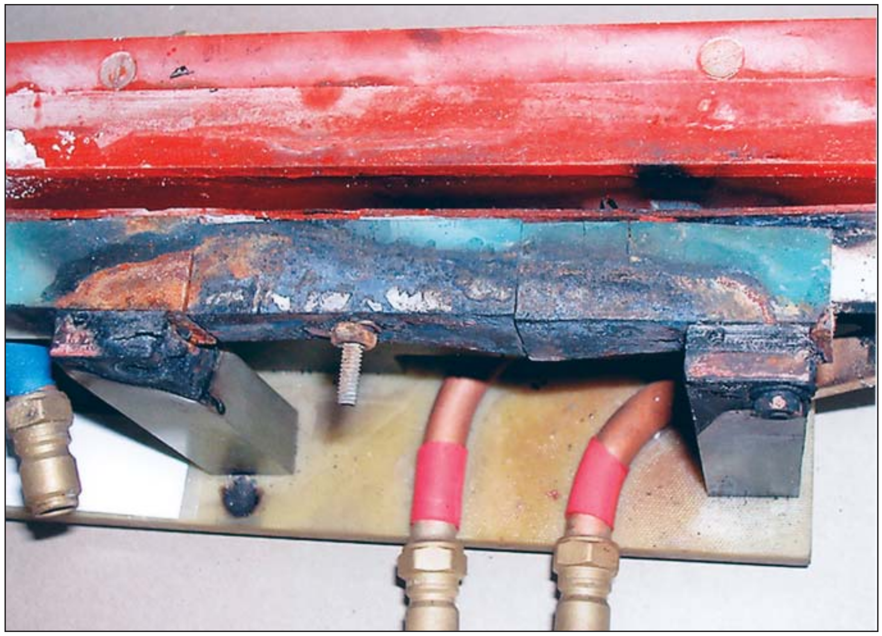

Fig. 3 — Degradation of a powder-based flux concentrator due to overheating.

Failure Due to Overheating

Degradation of the flux concentrator due to its overheating is the most typical failure mode (Fig. 3).

There are two causes of concentrator overheating: heat flow from the surface of the heated workpiece (due to thermal radiation and convection) and heat generated within a concentrator (due to power losses there). In the majority of induction hardening applications, the coil-to-workpiece air gap is typically in the 1/16 to 1/4 in. (1.6 to 6.35 mm) range. Since hardening temperatures are usually within the 1550 to 1800°F (845 to 980°C) range, depending on the application, there can be appreciable heating of a flux concentrator that is located in close proximity to the workpiece. In fact, concentrator temperature can exceed its maximum working temperature, which typically is relatively low; for example, 660°F (350°C) for powder materials (see Table). The result is significant overheating and premature failure (Fig. 3).

The binders that hold particles together in magnetic powder concentrators are often called dielectric binders. As a result, some mistakenly assume that a magnetic flux concentrator is a dielectric body (electrically nonconductive). In reality, they are far from being dielectric — their electrical resistivities are not infinite, but have some appreciable values. So, because they are electrically conductive, there will be some heat generated within them under an applied ac magnetic field. It is important to estimate the amount of that heat in order to make an intelligent decision regarding the cooling required to avoid overheating of the flux concentrator.

Laminations: Although laminations can withstand much higher working temperatures than powder-type concentrators, they can still be overheated, particularly in high-frequency induction applications.

Thermal expansion is closely related to the heat generated in both the magnetic flux concentrator and the inductor. Premature coil failure can result if insufficient attention is paid to thermal expansion. For example, a channel coil should be designed to accommodate any potential axial growth of the copper during heating. Similarly, lamination retainers should also take the thermal expansion factor into consideration.

Laminations also are sensitive to aggressive environments, such as quenchants. Rust and degradation can result (Fig. 4). The magnetic properties of laminations can be degraded by an increase in coercive force and subse-

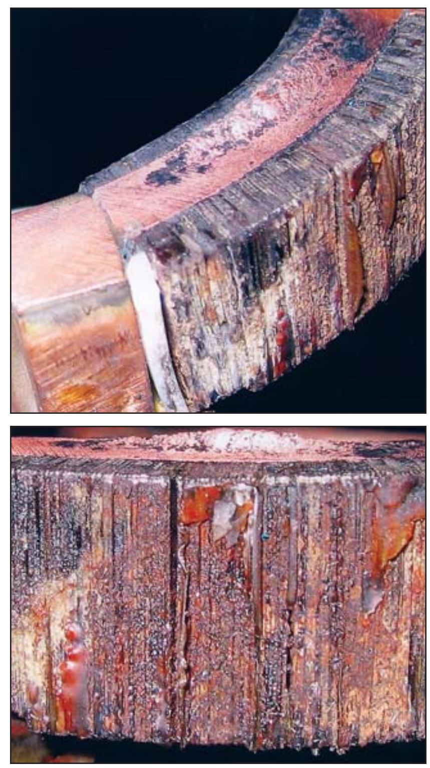

Fig. 4 — Laminations are particularly sensitive to aggressive environments such as quenchants. Rusting and degradation result.

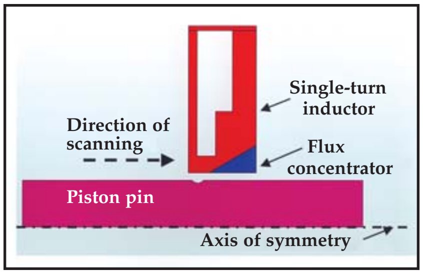

Fig. 5 — An induction scan hardening system with single-turn coil and magnetic flux concentrator.

quent hysteresis loss. And if the individual laminations are not firmly clamped together, they could start to vibrate, resulting in mechanical damage, copper marks, and eventual failure of the coil or process.

On the plus side, laminations are relatively inexpensive and can withstand high temperatures at low frequencies better than other materials. Another advantage is that laminations have the highest magnetic permeability (in strong magnetic fields) and saturation flux density (1.4 to 1.9 T) among flux concentrator materials. This means that laminations are better able to retain their magnetic properties in the strong magnetic fields typical of induction hardening.

Sharp corners: Avoid sharp corners, regardless of the type of flux concentrator, because of their tendency to saturate and/or overheat due to electromagnetic end effects (Figures 5 and 6). The initiation of fractures can almost always be minimized or eliminated by a well-thought-out coil design (Fig. 7). Computer modeling is essential to determine an optimal coil design.

It also may be possible to avoid overheating of corners and end-faces by designing a magnetic flux concentrating "system" that uses 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 the life of the concentrator because it takes into account the 3-D field distortion due to the electromagnetic end effect that would result in additional losses if laminations were used alone.

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

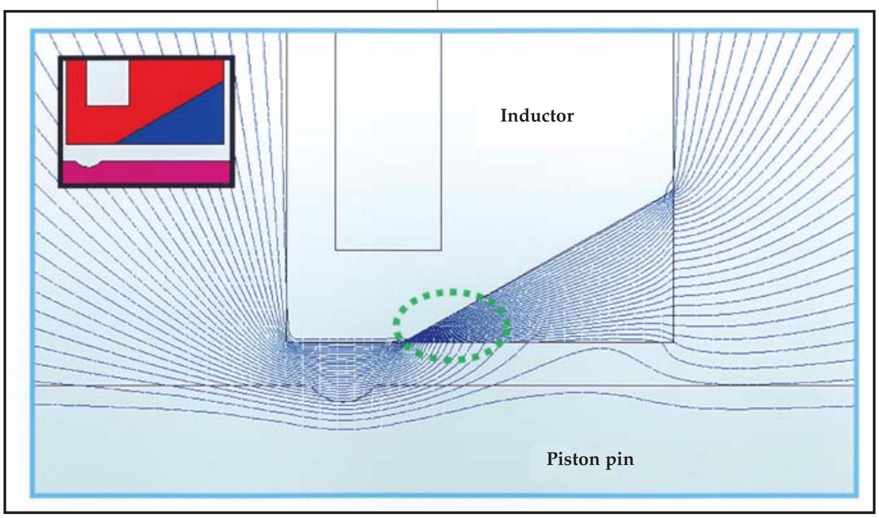

Fig. 6 — Magnetic field distribution in the scan hardening system sketched in Fig. 5. The sharp corner of the flux concentrator experiences the maximum flux density. This area is a prime candidate for saturation. In addition, it will be heated by thermal radiation and convection from the surface of the hot workpiece.

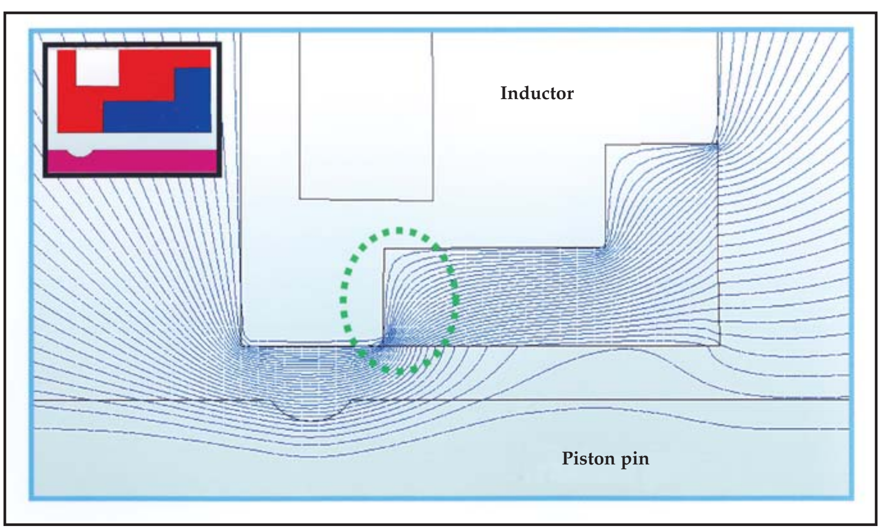

Fig. 7 — Magnetic field distribution with an improved flux concentrator design (compare with Fig. 6). Modifications included special coil profiling and elimination of sharp corners in areas where the magnetic flux density is high.

Installation and Stability

Another major concern with flux concentrators is the reliability of their installation. Concentrators typically are soldered, screwed, or glued to the induction coil.

Iron- and ferrite-based powder concentrators are often simply glued to the coil copper using "thermally conductive" adhesives. However, that label could be misleading. These adhesives actually have much poorer thermal conductivities than any metal. Users should not automatically assume that the adhesive's thermal conductivity is sufficiently high to provide the required cooling. If used, the thickness of the adhesive layer should be minimized to make the best of its ability to provide cooling from the water-cooled coil toward the surface of the flux concentrator.

There's another misconception that can lead to cooling-related failures. Some users mistakenly think that if the surface of a powder-type flux concentrator has good contact with the water-cooled inductor, then the entire flux concentrator will be sufficiently cooled. As already mentioned, iron- and ferrite-based powder flux concentrators incorporate special binders. Their thermal conductivities are typically even lower than those of so-called thermally conductive adhesives, resulting in the potential for localized overheating of certain areas of the concentrator, almost regardless of how well it is in contact with the water-cooled copper.

Forces: Flux concentrators are usually 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 out of position.[1,7]

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

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In the May/June 2006 issue, part 6 of this series will focus on how the electromagnetic end effect can influence inductor life. The electromagnetic end effect of an induction coil is defined by frequency, power density, coil-to-workpiece geometry, and the physical properties of the heated metal. It results from a distortion of the electromagnetic field in the end areas of the induction coil.

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.

Final words: Because a magnetic flux concentrator is attached to the induction coil, even having the best possible concentrator won't compensate for a poorly designed inductor. To take full advantage of a flux concentrator, the coil must be properly designed and fabricated.

There also is an expense associated with adding a flux concentrator to an existing inductor. A common saying among induction heating professionals is, "If a good part can be effectively produced without a flux concentrator, there is no reason to add to coil cost."

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