PROFESSOR INDUCTION

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Professor Induction welcomes comments, questions, and suggestions for future columns. Since 1993, Dr. Rudnev has been on the staff of Inductoheat Group, where he currently serves as group director – science and technology. In the past, he was an associate professor at several universities. His expertise is in materials science, metallurgy, heat treating, applied electromagnetics, computer modeling, and process development. Dr. Rudnev is a member of the editorial boards of several journals, including *Microstructure and Materials Properties* and *Materials and Product Technology.* He has 28 years of experience in induction heating. Credits include 16 patents and 128 scientific and engineering publications.

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Systematic analysis of induction coil failures

PART 7: FABRICATION OF HARDENING INDUCTORS

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 1–6 appeared in the August, September/October, and November/December 2005, and January/February, March/April, and May/June 2006 issues.

Copper is almost exclusively used for induction coils because of its cost, availability, and a unique combination of electrical, thermal, and mechanical properties.[1–4] Induction coils for hardening applications are typically CNC machined from a solid copper bar, thus making them rigid, durable, and repeatable. In other cases, copper tubing (rectangular or round) may be used for coil fabrication.

Brazed joints: Copper tubing is typically annealed to improve its ductility, bending properties, and workability. When sharp bends, complex coil shapes, or small diameters are required, components of coils made from tubing are assembled by brazing. Joints are often overlapped, creating so-called "tongue and groove" joints. CNC machined coils also use brazing to encapsulate water-cooling channels.

Different alloys (fillers) can be used for brazing of copper. Good wetting and free-flow characteristics are important. A silver-base brazing alloy that contains 35 to 45% Ag is commonly used for brazing coil parts.[1] The alloy flows well and has lower electrical resistance than the majority of other filler materials. To provide sound joints, the joint gaps (clearances) should be held to a minimum so that the silver-base alloy will freely flow into the joint due to capillary action.

Silver has superior electrical and thermal properties compared with copper, and the fact that joint gaps are filled by a silver-base material sometimes misleads induction heating practitioners into assuming that those fillers provide as good or almost as good electrical contact between brazed components as would be the case with solid copper. They do not.

Figure 1 is a sketch of coil current flow in the proximity of a brazed joint. Porosity and the presence of oxides and other elements increase the electrical resistance of the joint area compared with that of solid copper. As a result, there will be excessive joule losses and heat generation in the copper joint area (unless the joint is located in a portion of the coil that is not expected to carry electrical current). Excessive heat generation deteriorates brazed joints.

If the induction coil contains numerous brazed joints and, in particular, if there are 90° joints (like the one in Fig. 1), then water flow in cooling coil turns could be impeded. This problem is more likely to occur if small diameter tubing is used for coil fabrication. As a result, booster pumps may be needed to provide sufficient pressure for water cooling of the coil. However, there's a potential "Catch-22" associated with using booster pumps: Excessive pressure complements the electromagnetic forces and thermal stresses experienced by the coil copper.[1,5] This could further

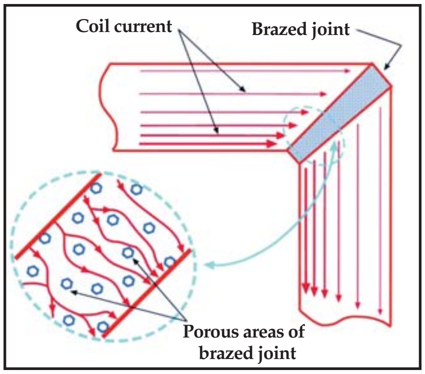

Fig. 1 — Coil current flow through a brazed joint in a copper inductor.

weaken coil braze joints and lead to cracking and water leaks.

Also, during the coil's service life, brazed joints as well as the copper itself may weaken due to work hardening, becoming brittle and developing fatigue cracks.

Bending is better: Elimination of braze joints or a dramatic reduction in their number, particularly in current carrying areas, is a key to fabricating durable, reliable, repeatable inductors. This can be accomplished by taking advantage of improvements in copper bending technology. An example is given in Fig. 2, which shows a length of rectangular copper tubing that was bent according to "know-how" recently developed by Inductoheat. Note that this small rectangular copper tubing — ¼ in. (6.4 mm) × ¼ in. (6.4 mm) and 0.04 in. (1 mm) wall — can be easily bent into a complex shape having 90° bends and can even be double twisted at angles of nearly 180°.

Use of this copper bending technology can have a significant positive effect on coil life and up-time of induction heating systems.

Other helpful hints: When designing and fabricating long-lasting induction systems it is important to consider the electromagnetic field in the immediate vicinity of the inductor. The use of low-resistivity nonferrous materials (preferably electrically nonconductive) in the area close to the inductor is recommended. Fasteners and washers used to connect bus-work to the inductor should also be nonferrous and preferably nonconductive. The rule of thumb: Ferrous materials should be located at least one coil diameter away from the coil. More precise recommendations can be obtained by using computer modeling.

The heating face wall thickness should increase as frequency decreases. This fact is directly related to the current penetration in the copper and the copper edge effect, and holds true for both coils machined from a solid copper bar and coils made of copper tubing.

A quick estimate of current penetration depth, δ_1, in the copper can be calculated using these formulas[1]:

$$\delta_1\text{, in.} = 2.75/(\mathit{frequency}\text{, Hz})^{1/2}$$

$$\delta_1\text{, mm} = 70/(\mathit{frequency}\text{, Hz})^{1/2}$$

An effective copper tubing wall (d_1) should be greater than $1.6\delta_1$.

A coil tubing wall thinner than $1.6\delta_1$ results in a reduction in coil efficiency. In some cases, the tubing wall (d_1) can be much thicker than $1.6\delta_1$. This is because it may be mechanically impractical to use a tubing wall thickness of, for example, 0.01 in. (0.25 mm). In addition to carrying the current, the coil assembly also serves other mechanical purposes such as cooling passage and quench pocket design, and providing support against mechanical flexing.

At higher frequencies, coil currents are typically lower. As frequency is reduced, more attention must be paid to coil support and brazed joints. There is also more vibration at lower frequencies. Nonmagnetic metal studs held together with an insulator can be used to provide added support.

Support, protection: After coil brazing, the rest of the inductor is assembled and any coil protection is added. There are several common ways to protect induction coils from the sometimes harsh environment in which they operate. In most heat treating applications, the workpiece surface is heated to above 900°C (1650°F). The intensive radiant heat from the part can be detrimental to the coil. With the hot workpiece located close to the coil — for example, having a copper-to-part gap of less than 1/8 in. (3.2 mm) — the design of the cooling passage is very critical.[1] Coil cooling should be as close to the heating face as possible, particularly if U-shaped flux concentrators are applied.

An epoxy coating is often applied between the turns of multiturn inductors for isolation purposes. A ceramic coating is often used for single-turn inductors. A thin layer of ceramic is flame sprayed onto a selected area of the inductor to improve its wear resistance and to serve as a thermal barrier. The ceramic also acts as an electrical insulator, in cases where the part could come in contact with the inductor.

In addition, ceramic guides or cast refractory liners can be added to the system, when space is available. If a liner is damaged, it can usually be easily replaced without having to remove the inductor from the heating system. This reduces equipment downtime in applications such as in-line hardening of multiple rods or tubes. Of course, this advantage comes at the expanse of having a greater copper-to-part gap, which negatively affects electromagnetic coupling and coil electrical efficiency.

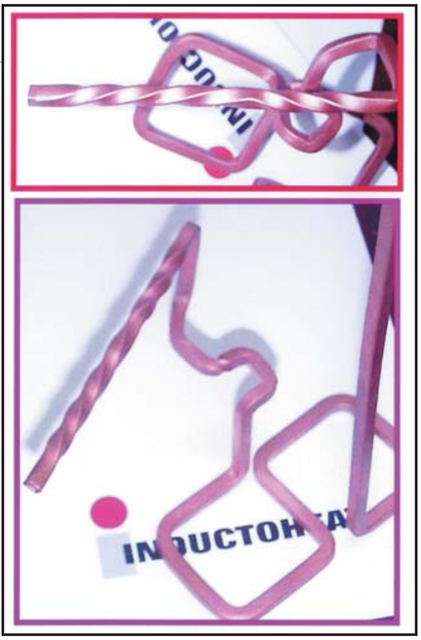

Fig. 2 — A length of rectangular copper tubing that was bent using "know-how" recently developed by Inductoheat. Note that this small rectangular copper tubing — ¼ in. (6.4 mm) × ¼ in. (6.4 mm) and 0.04 in. (1 mm) wall — can be easily bent into a complex shape.

References

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