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 6: COIL END EFFECT

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 1–5 appeared in the August, September/October, and November/December 2005, and January/February and March/April 2006 issues.

Nonuniform coil current density distribution resulting from various electromagnetic phenomena has a dramatic effect on induction coil life and crack development in the copper.[1–3] Coil end effect and copper electromagnetic edge effect are critical factors that should be taken into account when designing "long-lasting" induction coils. The coil copper edge effect that is primarily responsible for copper edge cracking was discussed in Part 4 of this series.[2] This column concentrates on the other important electromagnetic phenomenon: the coil end effect.

End Effect in Multiturn Coils

Experienced users of induction heating equipment that utilize multiturn coils are likely to have noticed that failure of a multiturn inductor is often associated with the failure of turns located at the ends of the coil. Arcing, copper overheating and even melting, development of a short circuit between turns, and liner and/or refractory disintegration are only a few of the failure modes observed at end turns that are related to the electromagnetic end effect.

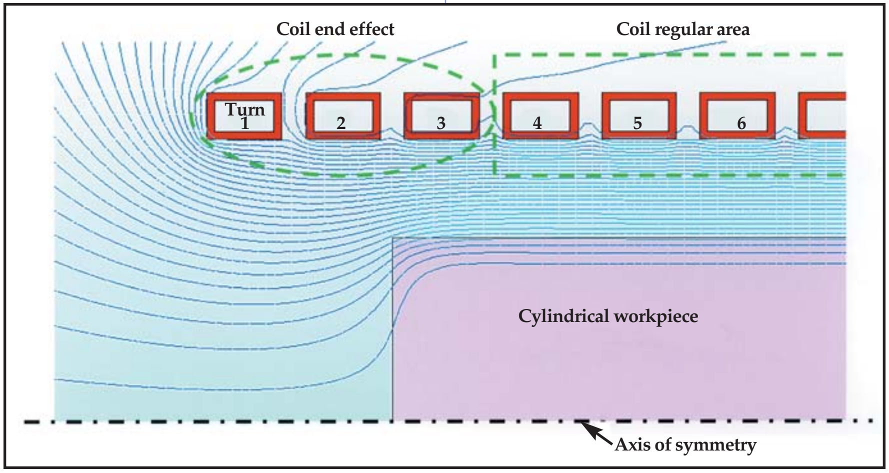

Fig. 1 — Magnetic field distribution in a multiturn induction coil showing the coil end effect.

Its cause: The coil end effect is due to a distortion of the electromagnetic field in the end areas of an induction coil (Fig. 1).

In areas of the coil away from its ends (the regular area), the magnetic field distribution can often be considered relatively uniform and homogeneous, particularly for electromagnetically long coils having large values of the space factor, K_{space}. As discussed in Ref. 1, the coil turn space factor indicates how tightly the coil turns were wound. For example, a single-turn coil has a space factor of 1. For the majority of multiturn inductors used in annealing, stress relieving, heating for forging, and other applications, $K_{space} = 0.7–0.9$. This means that coil turns are tightly wound and slight disturbances in the magnetic field between turns will not have a noticeable effect on the field distribution in the regular area of the coil (Fig. 1).

In contrast, distortion of the magnetic field at the coil end is dramatic, and affects several factors that can be

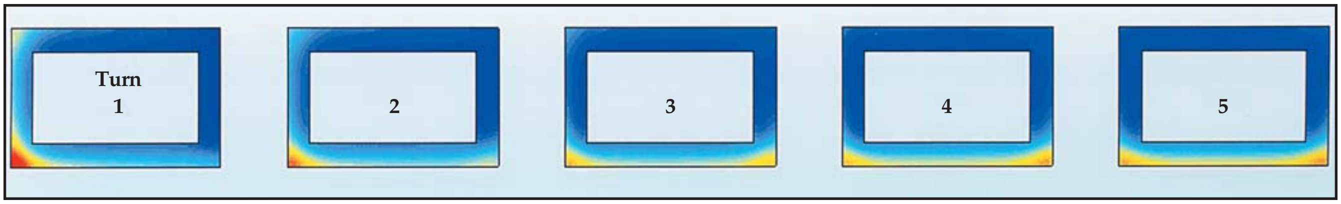

Fig. 2 — Current density distribution within coil turns in a multiturn induction coil. (Turn numbers correspond to those in Fig. 1.)

directly related to specific modes of premature coil failure in this area. Examples of these factors include:

- Distortion of current density distribution within those turns located in the coil end area (Fig. 2)[4]
- Redistribution of the power losses and voltage drops per turn
- Complex distribution of magnetic field force or magnetic field pressure experienced by turns

Need to Know Magnetic Forces

Figure 3 shows the distribution of magnetic force components experienced by the turns of the coil design shown in Fig. 1 (frequency = 3 kHz). In this particular case, the radial component of the magnetic force is minor and can be neglected in coil design. The greatest force experienced by Turn 1 is the axial component. This component gradually decreases, becoming as low as the radial component in the regular area of the coil, away from the end. Note, however, that the hoop component of the force gradually increases, reaching its maximum value in the regular area. Knowledge of the magnitude and orientation of magnetic forces is essential to preventing excessive vibration of coil turns, ensuring a durable, sound inductor.[5]

The magnetic field pattern in the coil end area is a complex function of several often-interrelated factors. These include but are not limited to:

- Electromagnetic properties of the heated metal. Is it magnetic or nonmagnetic? Is it a good or poor electrical conductor?
- The frequency and magnetic field intensity.
- Workpiece geometry.
- Specifics of coil design, including: coil overhang, "coil-to-workpiece" coupling, space factor of turns (K_{space}), coil copper profile and size of turns, presence of magnetic flux concentrators and shunts, and presence of Faraday rings, flux extenders, and other similar devices.

It is important to remember that, depending upon the application, these factors can have different impacts. Although each application should be considered individually, there are some general recommendations or tendencies. For example, power losses within the coil end turns are typically greater when heating nonmagnetic metals that have low electrical resistivities than when heating magnetic materials that have high resistivity values. This phenomenon should be taken into consideration when designing coil water-cooling circuits.

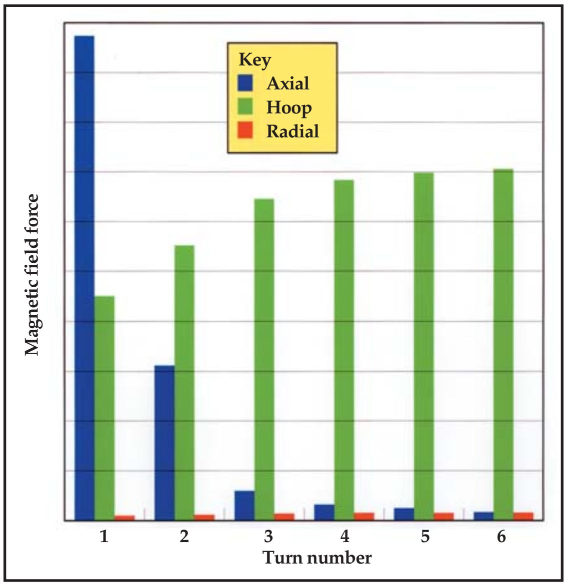

Fig. 3 — Distribution of the three components of magnetic field force along the turns of a multiturn induction coil. (Turn numbers correspond to those in Fig. 1.)

Even such frequently overlooked parameters as the profile of the coil turns (their height and width) could in some cases have a noticeable effect on field force and power loss distribution along the turns.

Modeling will help: Computer modeling has the capability to predict how numerous interrelated factors will affect coil performance. A coil manufacturer or process developer who can accurately identify the "weakest link" of a particular coil design and then determine what must be accomplished to optimize coil life has a considerable advantage over the traditional processes of simply guessing and/or carrying out numerous trials based on experience gained from past mistakes. Computer modeling shortens the design cycle, saves prototyping time and money, and facilitates the manufacture of long-lasting induction coils.

Q&A next: In the next issue of *HTP*, Professor Induction will field selected questions from readers about the subjects discussed in previous installments.

References

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