Systematic analysis of induction coil failures

PART 4: COIL COPPER ELECTROMAGNETIC EDGE EFFECT

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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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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 - 3 appeared in the August, September/October, and November/December 2005 issues.

Nonuniform coil current distribution resulting from various electromagnetic phenomena has a dramatic effect on induction coil life and crack development in the copper. Some of these phenomena were discussed in References 1 and 2. The coil end effect and copper electromagnetic edge effect are two other important factors that should be taken into account when designing durable induction coils.

End effect is defined by frequency, power density, coil-to-workpiece geometry, and the physical properties of heated metal. It results from a distortion of the electromagnetic field in the end areas of the induction coil. Coil end effect will be the focus of another installment in this series. This column is devoted to the coil copper electromagnetic edge effect.

Electromagnetic Edge Effect

Experienced users of induction heating equipment are likely to have noticed that failed inductors often have cracks in the copper edge areas (Fig. 1). The electromagnetic edge effect is a major contributor to this copper edge cracking. Note that the copper edge area is a special region from both the electromagnetic and thermal perspectives. The edge is also a natural stress raiser.

Frequency: Figure 2(a) shows a single-turn coil that is used for induction static hardening of shafts. It was fabricated of rectangular copper tubing, 0.75 x 0.33 in. (19 x 8 mm) with a 0.04 in. (1 mm) wall. A plot of the electromagnetic field distribution around the coil is shown in Fig. 2(b). Coil design details, properties of the heated metal, workpiece geometry, and the applied frequency have noticeable effects on the current distribu-

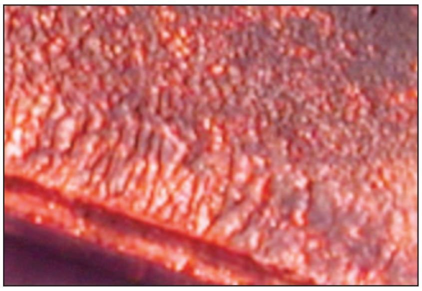


Fig. 1 — Crack initiation in the edge areas of a copper induction coil.

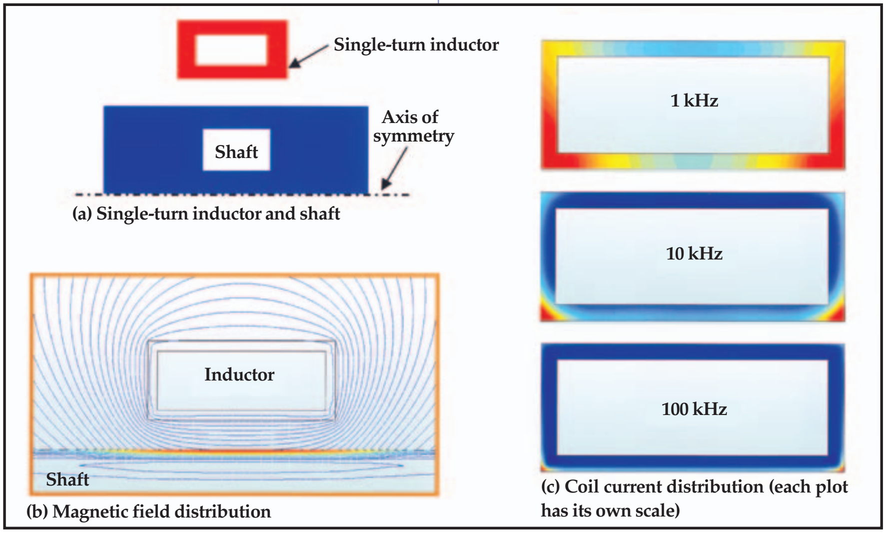


Fig. 2 — The electromagnetic edge effect and how applied frequency affects it, in a single-turn induction coil made of rectangular copper tubing.

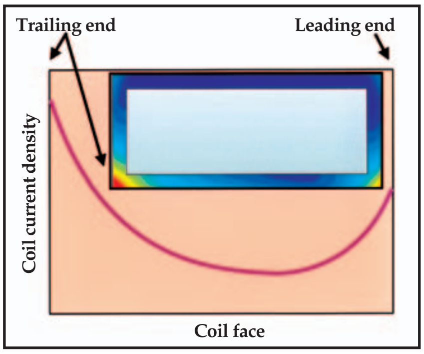
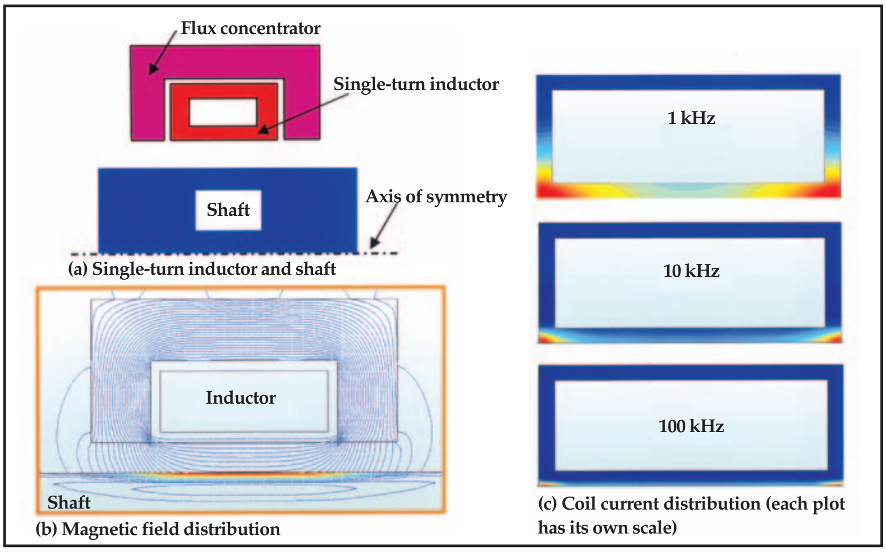


Fig. 3 — Coil current distribution during induction scan hardening of a shaft.



(a) Single-turn inductor and shaft

(b) Magnetic field distribution

(c) Coil current distribution (each plot has its own scale)

Fig. 4 — The effect of a U-shaped magnetic flux concentrator on the electromagnetic edge effect in a single-turn induction coil. Compare with Fig. 2.

tion within the induction coil copper.

At the same time, practically regardless of the applied frequency, there will always be a greater concentration of current density in the edge areas of the coil copper and, in particular, at the "inside" coil corners that face the heated workpiece. This is shown in Fig. 2(c).

There is also a slight concentration of current at the "outside" corners of the coil, but as frequency increases this concentration becomes less pronounced and eventually practically disappears.

Figure 2(c) shows that high frequency leads to a higher current density concentration at the inside coil corners. This "edge-catching" effect of coil current can result in "hot spots" at the coil copper corners. The combination of surplus current density at natural stress raisers makes these inside corners primary potential crack initiation sites, particularly if cooling is insufficient.

Note that for visualization purposes each plot of current distribution in Fig. 2(c) has its own scale. The current penetration depth into copper at 100 kHz is 10 times smaller than at 1 kHz: 0.216 mm vs. 2.16 mm (0.0085 in. vs. 0.085 in.), respectively. Therefore, localized current density at 100 kHz would be much greater than at 1 kHz (assuming that total coil current is the same).

Factors Affecting Edge Effect

Figure 2 shows that frequency has a significant impact on the electromagnetic coil copper edge effect. However, choice of frequency is typically dictated by the application and heat pattern requirements and cannot be easily changed.

Coil geometry is another factor that has an appreciable effect on the electromagnetic edge effect. Even if the same copper alloy and copper tubing geometry are used for a given coil, the design of the inductor — split-return coil, pancake-type inductor, or hairpin coil, for example — could significantly affect the coil current distribution and the appearance of the copper edge effect. As discussed in Ref. 3, the current distribution in ID (inside diameter) coils is dramatically different from that for inductors used to heat external surfaces.

Properties: Physical properties of heated metals, including electrical conductivity and magnetic permeability, can also impact copper current distribution. For example, if identical coils are used for both induction scan and static hardening, the current distributions will be quite different for the two hardening methods.

In scan hardening, the region of the workpiece that is located near the coil leading end has a temperature below the Curie point. Therefore, the leading end of the coil mainly "sees" magnetic material having relatively low electrical resistivity. In contrast, the steel is nonmagnetic under the coil trailing end because its temperature exceeds the Curie point and, therefore, has much higher electrical resistivity. The result is a shifting of the maximum coil current density toward the trailing end area of the coil ID corner (Fig. 3).

Failure site: In addition to experiencing the maximum current density concentration, the coil trailing edge is exposed to much greater heat from the surface of the heated workpiece (due to thermal radiation and convection) than is the leading edge. These factors combine to make the coil trailing edge the most likely site for crack initiation of any region of the scan hardening inductor.

Next: Flux Concentrator Effect

Accessories and tooling also can have appreciable effects on the magnetic field and coil current distribution. For example, use of U-shaped magnetic flux concentrators results in a noticeable redistribution of coil current that has a tendency to further increase current density at coil edges (Fig. 4). The electromagnetic properties and geometry of a flux concentrator are factors that affect how it impacts the coil copper edge effect.

Part 5 of this series will discuss an effect of magnetic flux concentrators on induction coil life.

References

1. *Handbook of Induction Heating*, by V. Rudnev, D. Loveless, R. Cook, and M. Black: Marcel Dekker Inc., New York, 2003, 800 p.

2. "Systematic Analysis of Induction Coil Failures, Part 2: Effect of Current Flow on Crack Propagation," by V. Rudnev: *Heat Treating Progress*, Vol. 5, No. 6, September/October 2005, p. 33–35.

3. "Designing Inductors for Heating Internal Surfaces, by V. Rudnev: *Heat Treating Progress*, Vol. 5, No. 1, January/February 2005, p. 23–25.