by Valery I. Rudnev • Inductoheat Group

Systematic analysis of induction coil failures

PART 2: EFFECT OF CURRENT FLOW ON CRACK PROPAGATION

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. Part 1 appeared in the August issue.

This entry in the series begins with a discussion of skin effect and how it concentrates current in a thin surface layer of the conductor.

Current and the Skin Effect

When an alternating current flows through a conductor (that is, bus bar), the current distribution is not uniform. Due to the skin effect in the current-carrying metal, the maximum value of the current density will decrease from the surface of the conductor toward its interior (Fig. 1).

Because of this effect, approximately 63% of the current will be concentrated within the surface layer of the conductor at what is called the penetration depth. Current penetration depth in copper depends upon the electrical resistivity of the alloy and current frequency.

Table 1 shows variation of the penetration depth in pure copper with frequency at ambient temperature (20°C, 68°F). For example, if a 0.25 in. (6.35 mm) thick solid copper bar carries a current of 2000 A at a frequency of 30 kHz, in reality the great majority of that current (about 1260 A) will be concentrated within a thin layer less than 0.5 mm (about 0.02 in.) thick. The rest of the copper bar primarily serves mechanical purposes, including providing resistance to flexing and bending.

Table 1 — Current penetration depth into pure copper vs. frequency

Frequency, kHz	Penetration depth, mm
1	2.16
3	1.20
10	0.68
30	0.39
70	0.26
200	0.15
500	0.10

The Proximity Effect

Another electromagnetic phenomenon that dramatically affects the current distribution within a current-carrying conductor is the proximity effect. Details about this effect are discussed in Ref. 1. Figure 2 shows the current distribution in copper bars when electrical currents flow in opposite directions (a) or in the same direction (b).

The skin and proximity effects — as well as the "ring," "slot," and edge effects[1] — lead to a nonuniform current distribution within a copper coil. Areas of high current density within this distribution are the primary candidates for localized hot spots, which can result in premature coil failure.

Crack Propagation Specifics

In the majority of induction heating applications, the combination of the previously mentioned electromagnetic phenomena results in a current

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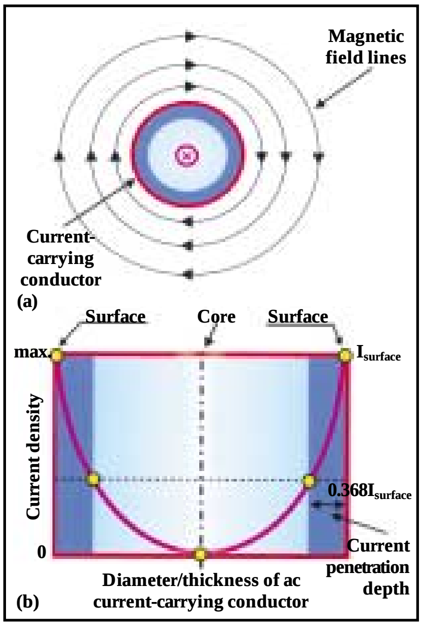

Fig. 1 — Current density distribution due to the skin effect. (a) Schematic of a single current-carrying conductor. (b) The nonuniform distribution of current, I, within that conductor.

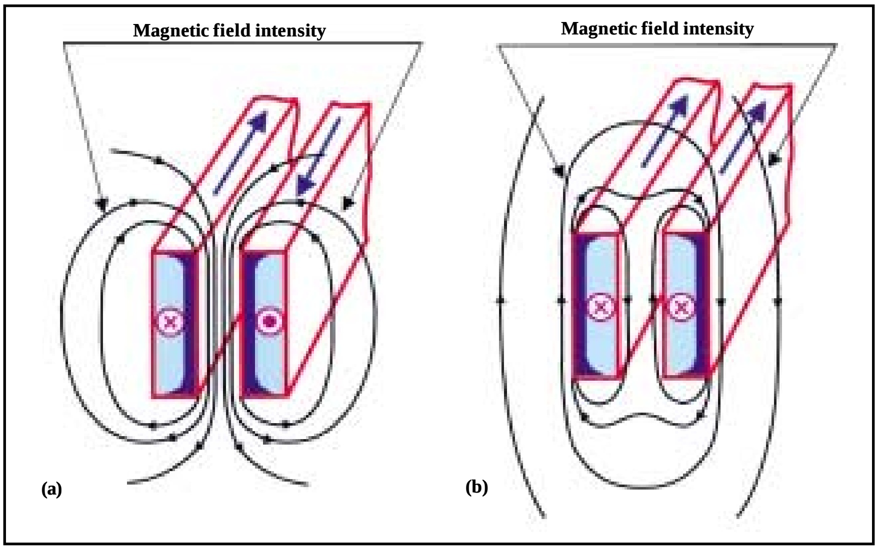

Fig. 2 — Current distribution in current-carrying copper bars due to the proximity effect. (a) Currents flowing in opposite directions. (b) Currents flowing in the same direction.

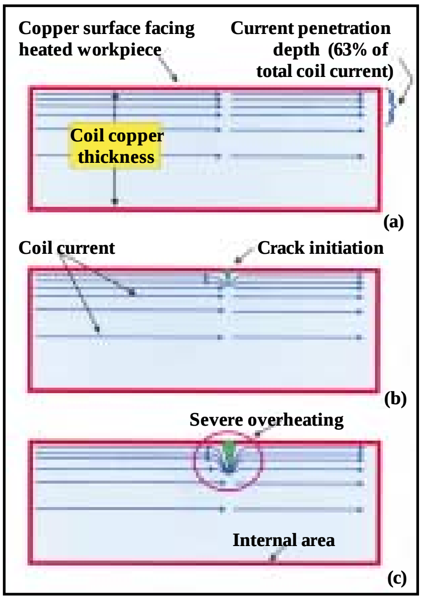

Fig. 3 — Crack development across copper coil thickness. (a) Normal flow of coil current. (b) A crack blocks normal current flow, causing it to detour around it. (c) As crack growth accelerates, it is accompanied by severe overheating at the crack root.

concentration within a thin layer of the coil surface that faces the heated workpiece. This is where the great majority of coil cracks initiate.

Figure 3 shows how a crack develops across the copper thickness (assuming that the workpiece is located above the coil copper). As already noted, for most of the frequencies utilized in induction heat treating (see Table 1), a majority of the coil current occupies a very thin surface layer. This is why even a small notch can become a crucial stress raiser that results in an abnormal current flow.

Figure 3(a) shows a normal flow of coil current. However, that normal flow will be disturbed by a fine crack, deep scratch, or tool mark on the surface of the coil. Figure 3(b) shows how a crack blocks normal current flow, resulting in the appearance of a localized flow anomaly — the current at the surface is forced to take a deep detour around the crack. As a result, the current density will be at a maximum at the crack root, where additional heating takes place.

This abnormal current flow in combination with excessive heat generation creates a condition favorable for crack opening. Similar to a “snowball” effect, further acceleration in crack growth will then take place, and it will be accompanied by increased severity of localized overheating of the crack root area, as shown in Fig. 3(c), and a reduction of coil mechanical strength at the crack root.

Cracks Deepen and Widen

To complete the study of the effect of current flow on coil crack development, it is important to keep in mind that in reality, crack propagation has a three-dimensional nature and all the electromagnetic phenomena discussed here have complex interactions. Therefore, not only does the crack deepen as it propagates, but it also widens. Figure 4(a) shows that a similar snowball effect takes place during crack development across the width of the coil copper that faces the heated workpiece.

From the very beginning, the crack blocks the normal current distribution and forces the current to flow around the crack. This leads to a current density surplus at the crack edges. Excessive current density produces extreme heat at the crack edges and the appearance of hot spots that, in turn, reduce coil copper strength there and create a condition favorable for further acceleration of crack widening, as shown in Fig. 4(b–d).

This leads to the conclusion that, in addition to other factors, the direction of the coil fracture often has a specific relationship to coil current flow.

Therefore, it can be appreciated that

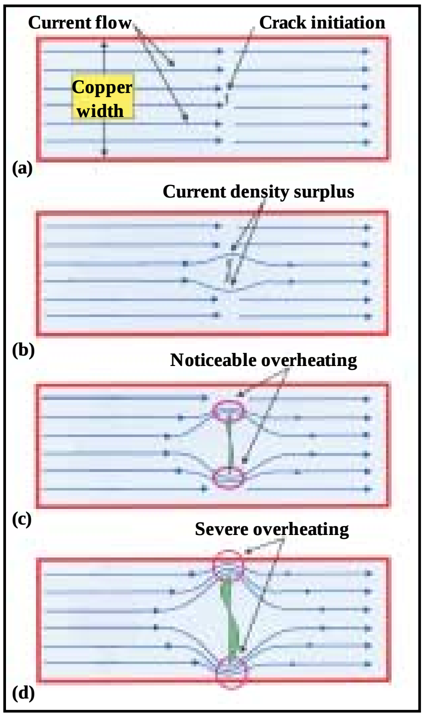

Fig. 4 — The “snowball” effect during crack development across the width of the coil copper face. While the crack widens (a–d), it also deepens (see Fig. 3).

surface discontinuities resulting from improper fabrication technique or assembly can have a dramatic negative effect on coil life. Damage to the current-carrying coil surface, be it preexisting cracks, tool marks, notches, or other stress raisers, should be avoided.

Two Coil-Abuse Case Studies

Abnormal service conditions that result in mechanical damage to a coil is one of the most typical factors that lead to premature coil failure. An example is shown in Fig. 5, where a coil's inside diameter was damaged during part loading, resulting in abnormal current flow, fast crack growth, and eventual coil fracture. Failure initiated at the damaged area.

Figure 6 shows another example of coil abuse resulting in severe copper surface damage. The horseshoe-shaped portion of the single-shot (channel) coil has numerous marks and scratches. The coil had been used for hardening the spline area of shafts. Most likely, a shaft was not properly located in the heating position. Sensors that are supposed to detect improper shaft positioning either failed to detect it or had been disconnected for some reason. The scratches resulted from the rubbing of the shaft spline against the induction coil during either loading/unloading or shaft rotation. As would be expected, those scratches dramatically reduced coil life, culminating in premature coil failure.

Alloy selection next: Selection of the proper material to be used for a coil is another vital factor that can have a considerable effect on inductor life. The subtle aspects of coil copper selection will be discussed in Part 3.

Reference

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

Fig. 5 — Severe damage to this coil's inside diameter resulted in abnormal current flow, a decrease in mechanical strength at the damaged area, and eventual fracture.

Fig. 6 — The horseshoe-shaped portion of this single-shot (channel) coil has numerous scratches resulting from improper locating of a splined shaft in the heating position. As a result, coil life was dramatically reduced.