PROFESSOR INDUCTION

by Valery I. Rudnev • Inductoheat Group

Designing inductors for heating internal surfaces

Induction heating of the internal surfaces of a workpiece for applications such as hardening, tempering, annealing, shrink fitting, and brazing has several unique features related to the physics of the process and the selection of process parameters, compared with heating of external surfaces.[1]

Figure 1 shows four main coil styles for heating internal surfaces: solenoid-type cylindrical coils (single-turn and multiturn), rod-type coils, hairpin inductors (single or double), and "C"-core coils.

This column reviews design features of solenoid-type internal coils (also called inside diameter or ID coils), which are the most popular inductors for heating internal surfaces.

Solenoid-type coil basics

Single-turn and multiturn solenoid-type inductors are often used for heating IDs of hollow parts. The inductors typically are made from copper tubing that is spiral wrapped the same way a solenoid is wrapped.[1] In some cases, the head of the internal inductor is machined from a solid copper bar. This not only provides a very rigid and robust coil, but also allows profiling of the coil to match a specific part's geometry.

Effectiveness of an internal cylindrical coil depends to a much greater extent on the coil-to-workpiece gap, compared with similar coils used for heating external surfaces or outside diameters (ODs). Electrical efficiency of an internal coil rapidly decreases with an increase in the coupling gap, particularly when heating nonmagnetic metals. To keep the coil-to-workpiece gap as small as possible the return leg is usually located inside of the internal coil.

Coil efficiency: Regardless of the design features, solenoid-type inductors for heating IDs are not as efficient as similar inductors used for heating ODs. This phenomenon is due to the electromagnetic "ring" effect.[1] According to this effect, the coil current is concentrated on the ID of the coil. When heating inside diameters this is the area farthest from the part. As a result, the electromagnetic coupling between coil and heated part is greater than the actual air gap between the ID of the workpiece and the coil's OD. This makes for poor coil-to-workpiece coupling and, therefore, causes a noticeable reduction of coil efficiency.

To improve coil-to-workpiece electromagnetic coupling, use small-diameter, thin-wall copper tubing, or flattened or rectangular tubing.

Heat distribution: Uniform winding of turns often results in deeper heat penetration in the middle of the workpiece and a shallower heat depth in the workpiece end areas due to the electromagnetic end effect.[1] Nonuniform heat distribution is particularly

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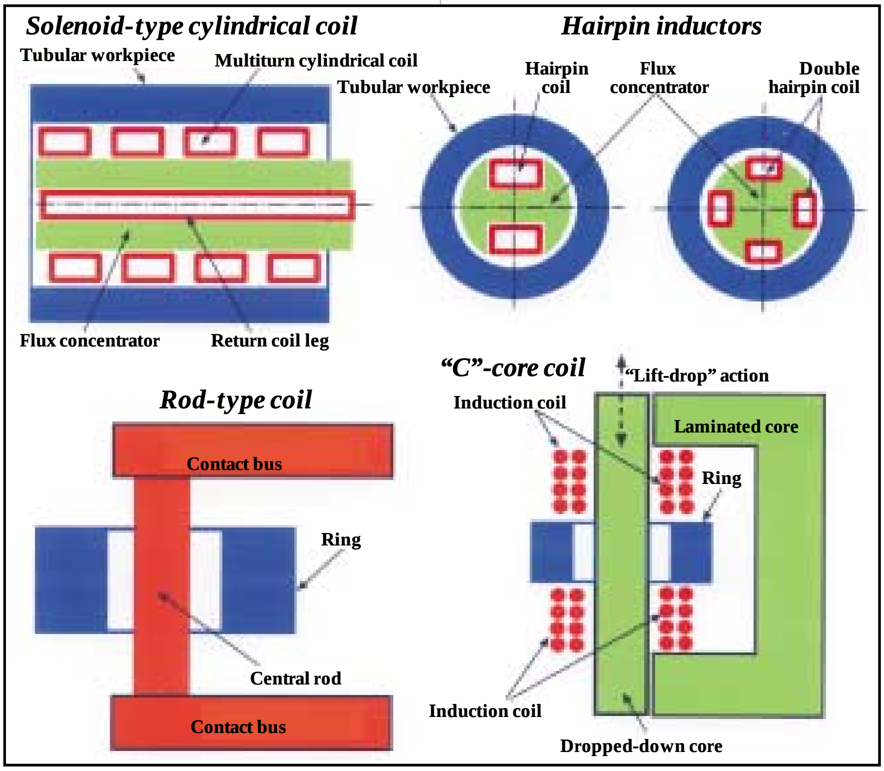

Fig. 1 — Four coil styles for induction heating of internal surfaces. Solenoid-type cylindrical coils are the most widely used. Both single-turn and multiturn inductors are produced.

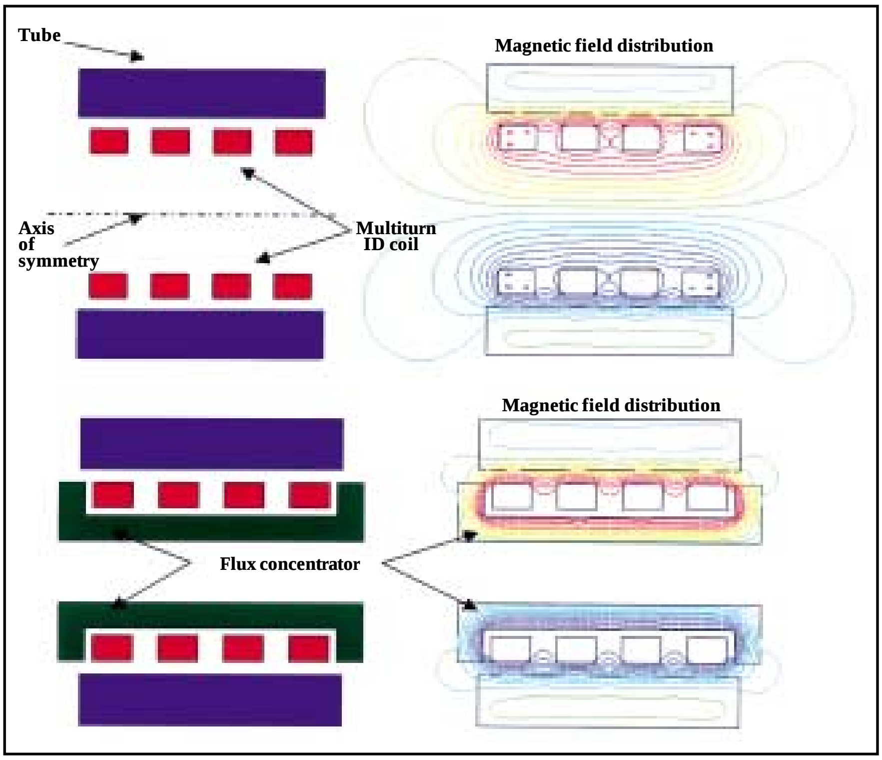

Fig. 2 — Effect of a flux concentrator (bottom) on the magnetic field distribution when heating the ID of a tube using a multiturn solenoid-type internal inductor.

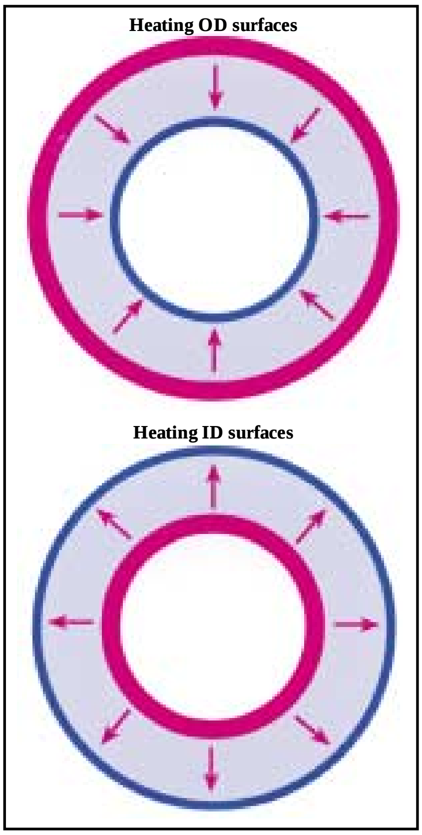

Fig. 3 — During OD heating, heat penetrates from a larger perimeter area toward a smaller perimeter area. The reverse is true when heating internal surfaces: heat propagates from a smaller perimeter area toward a larger perimeter area, resulting in a much greater "cold sink" effect.

noticeable when heating magnetic metals, resulting in a distinctive "thumbnail" heat pattern.

Heat source and temperature deficiencies in the workpiece end areas can be compensated for by increasing coil overhang and / or by spreading out middle turns of the coil in comparison with end turns.

Flux concentrators: Installing a magnetic flux concentrator inside of the internal inductor is frequently mandatory for improving electromagnetic coupling and increasing coil efficiency, particularly for small and moderate coil diameters.[1,2] The flux concentrator forces the maximum coil current density to be shifted closer to the heated workpiece, increasing magnetic field strength and heat intensity at workpiece internal surfaces (Fig. 2). Use of magnetic flux concentrators on internal coils provides noticeable reductions in required coil current and voltage and often simplifies load matching of induction coil and inverter. At the same time, an increase of the inside diameter of the heated part makes these improvements less pronounced.

It is important to remember that a magnetic flux concentrator is frequently considered to be the "weak link" of an ID coil. This is due to the potential for magnetic saturation of the concentrator material and its subsequent overheating, which could result in premature degradation of the inductor and a shortening of its life. Careful evaluation of process parameters and computer modeling will help prevent premature failure of the flux concentrator.

OD vs. ID heating

Figure 3 shows the fundamental difference in heat propagation in the workpiece when heating ODs and IDs. When induction heating OD surfaces, heat generated within the surface layer (at a specific current penetration depth) propagates toward internal areas due to the thermal conductivity of the metal. In contrast, when heating internal surfaces, the current penetration depth is located in the ID area, and the heat generated within that area propagates due to thermal conduction toward the OD of the workpiece.

'Cold sink' effect: As shown in Fig. 3, when OD heating the heat penetrates from a larger perimeter or circumferential area toward a smaller perimeter area. The reverse is true when heating internal surfaces: heat propagates from a smaller perimeter area toward a larger perimeter, resulting in a much greater "cold sink" effect.[1]

To compensate for this, why not use a lower frequency when heating IDs to increase the eddy current penetration depth? However, in the great majority of case hardening applications, to provide the same case depth, higher frequencies are used for induction hardening internal surfaces of parts than for outside surfaces. In addition, higher power densities are usually required to compensate for the loss in coil efficiency.

Higher-than-expected frequencies allow the coil current to be reduced, which is essential for cooling the copper coil, particularly when heating internal surfaces having relatively small diameters. Reducing coil current also helps to eliminate or reduce magnetic saturation of flux concentrators.

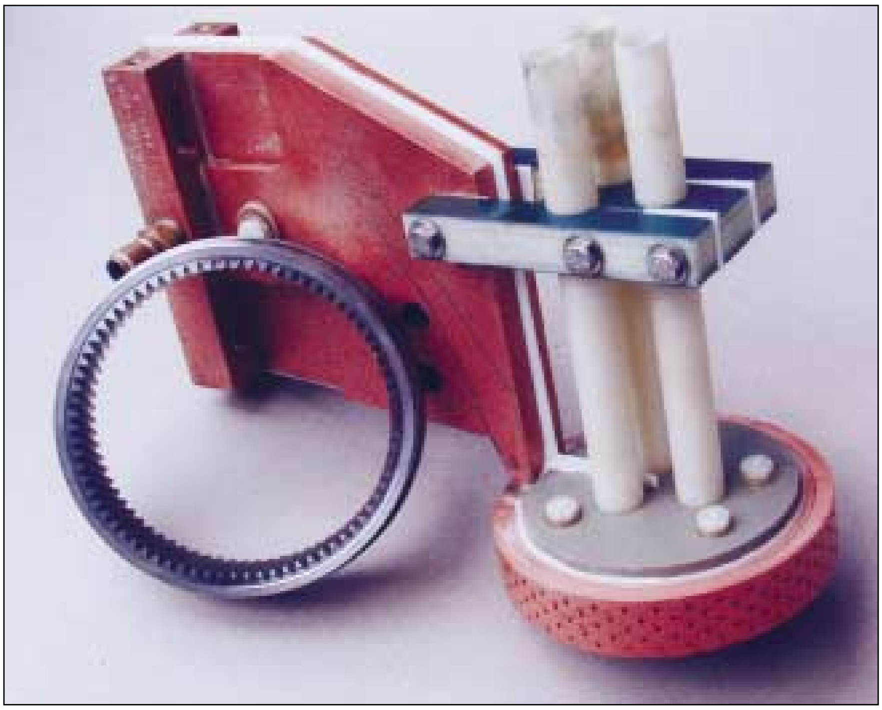

Fig. 4 — An internal inductor for hardening an internal ring gear (at left) for an automotive transmission. Coil cooling and quench holes are integrated in the head of the machined integral quench (MIQ) inductor. Photo courtesy Inductoheat Inc.

In addition, heat source intensity (eddy current density) is directly related to frequency, which makes it easy to generate a denser magnetic field in the workpiece surface by using a higher frequency.

These process features contribute to an ID surface temperature that typically is higher than that of an OD surface, assuming that heating time and case depth are the same for both.

Cooling: Coil cooling is another factor that greatly affects the life of internal inductors. In many cases, high-pressure pumps are used with ID coils to provide adequate cooling water flow. And in the machined integral quench (MIQ) design, coil cooling and quench holes are integrated in the head of the internal inductor. An example is shown in Fig. 4, a single-turn MIQ inductor used to harden an internal helical ring gear for an automotive transmission.[1] Specifics of coil cooling are discussed in Ref. 1.

Small-diameter holes

The main restriction to using solenoid-type internal coils is the difficulty of heating small-diameter holes. Because the return leg of the inductor usually goes through the center of the coil and because the magnetic flux concentrator must be installed inside of the coil, the smallest internal cylindrical coil OD is usually limited to about 5/8 in. (16 mm), but 0.75 in. (20 mm) is more typical. If the inside diameter of the heated part is smaller than 0.75 in. (20 mm), then rod-type or single- or double-hairpin inductors can be selected.[1] However, if these coils are used, the workpiece must be rotated during heating.

"C"-core inductors provide simultaneous heating of ID and OD surfaces. They are discussed in detail in Ref. 1.

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. "An Objective Assessment of Magnetic Flux Concentrators," by Valery I. Rudnev: Professor Induction column, *Heat Treating Progress*, Vol 4, No. 6, Nov./Dec. 2004, p. 19–23.