KEYS TO LONG-LASTING HARDENING INDUCTORS: EXPERIENCE, MATERIALS, AND PRECISION

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Induction coils are considered the weakest link in an induction hardening system, so advanced designs and precise fabrication are paramount to ensure long life while producing high quality treated parts.

The terms hardening inductor, inductor, induction coil, and coil are all used interchangeably to describe the electrical component that provides the induction heating effect in an induction heating system. A hardening inductor is often simply called a coil, but its geometry does not always resemble the classic circular coil shape. Figure 1 shows a sample of numerous coil designs. A particular coil configuration depends on several factors such as workpiece geometry, temperature uniformity and required heat pattern, and production rate, among others. Alternating current flowing in the inductor generates a time-varying magnetic field that provides an electromagnetic link between the inductor and workpiece, resulting in contactless heating of either the entire workpiece, or selected areas.

Coils are considered the weakest link in an induction hardening system because they carry significant electrical power and operate in harsh environments exposed to high temperatures, water, and other coolants, while being subjected to mechanical movement and sudden part contact. Advanced coil designs and precise fabrication can ensure long life while producing high quality treated parts.

MATERIAL SELECTION

Copper and copper alloys are almost exclusively used to fabricate induction coils due to their reasonable cost, availability, and a unique combination of electrical, thermal, and mechanical properties. Proper selection of copper grade and purity for a coil is crucial to minimize the deleterious effects of factors that contribute to premature coil failure including stress-corrosion and stress-fatigue cracking, galvanic corrosion, copper erosion, pitting, water leaks, overheating, and work hardening. Cooling water pH also affects copper susceptibility to cracking.

Oxygen-free high-conductivity (OFHC) copper should be specified for most hardening inductors despite its higher cost. Besides superior electrical and thermal properties, OFHC copper dramatically reduces the risk of hydrogen embrittlement. The higher ductility of OFHC copper is also important, because coil turns are subjected to flexing and high electromagnetic forces. The higher cost of OFHC copper usually is offset by improved hardening inductor life.

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FABRICATION TECHNIQUES

Two traditional techniques used to fabricate hardening inductors are banding and brazing of square, rectangular, and round copper tubing. The ability to precisely and repeatably fabricate banded or brazed inductors of complex geometry has always been a legitimate concern, which requires an extensive and costly validation process after installing a new set of inductors.

Silver-base braze material is used to fill joint gaps in brazed copper tubing. The fact that electrical and thermal properties of pure silver are superior to those of copper has led some coil builders and practitioners to assume that the filler metal provides electrical contact between brazed components as good as with solid copper, which is not the case.

Porosity and the presence of oxides and other elements increase the electrical resistance of the brazed joint area compared with that of solid copper. As a result, excessive heat is generated in the copper joint area, unless the joint is located in a portion of the coil that does not carry electrical current. Excessive heat generation causes deterioration of brazed joints, shortening coil life.

A complex geometry inductor that contains numerous brazed joints, and 90° joints in particular, could experience impeded water flow in cooling coil turns, a problem more likely to occur in a coil fabricated with small-diameter tubing. This situation could require the use of booster pumps to provide sufficient water pressure to cool the coil. However, this can be counterproductive as excessive water pressure adds to the electromagnetic forces and thermal stresses experienced by the copper coil, which could further weaken brazed joints, leading to cracking and water leaks. Also, brazed joints and the copper itself can weaken due to work hardening during coil service, becoming brittle and developing fatigue cracks. Eliminating or significantly reducing the number of brazed joints, particularly in current-carrying areas, is a key factor in fabricating long-lasting inductors.

CNC MACHINING AND QUALITY ASSURANCE

At Inductoheat, most high power-density hardening inductors are CNC machined from a solid copper bar regardless of complexity. This repeatable machining process produces rigid, durable inductors. CAD/CAM/CNC software programs are created that provide appropriate cutter-to-copper

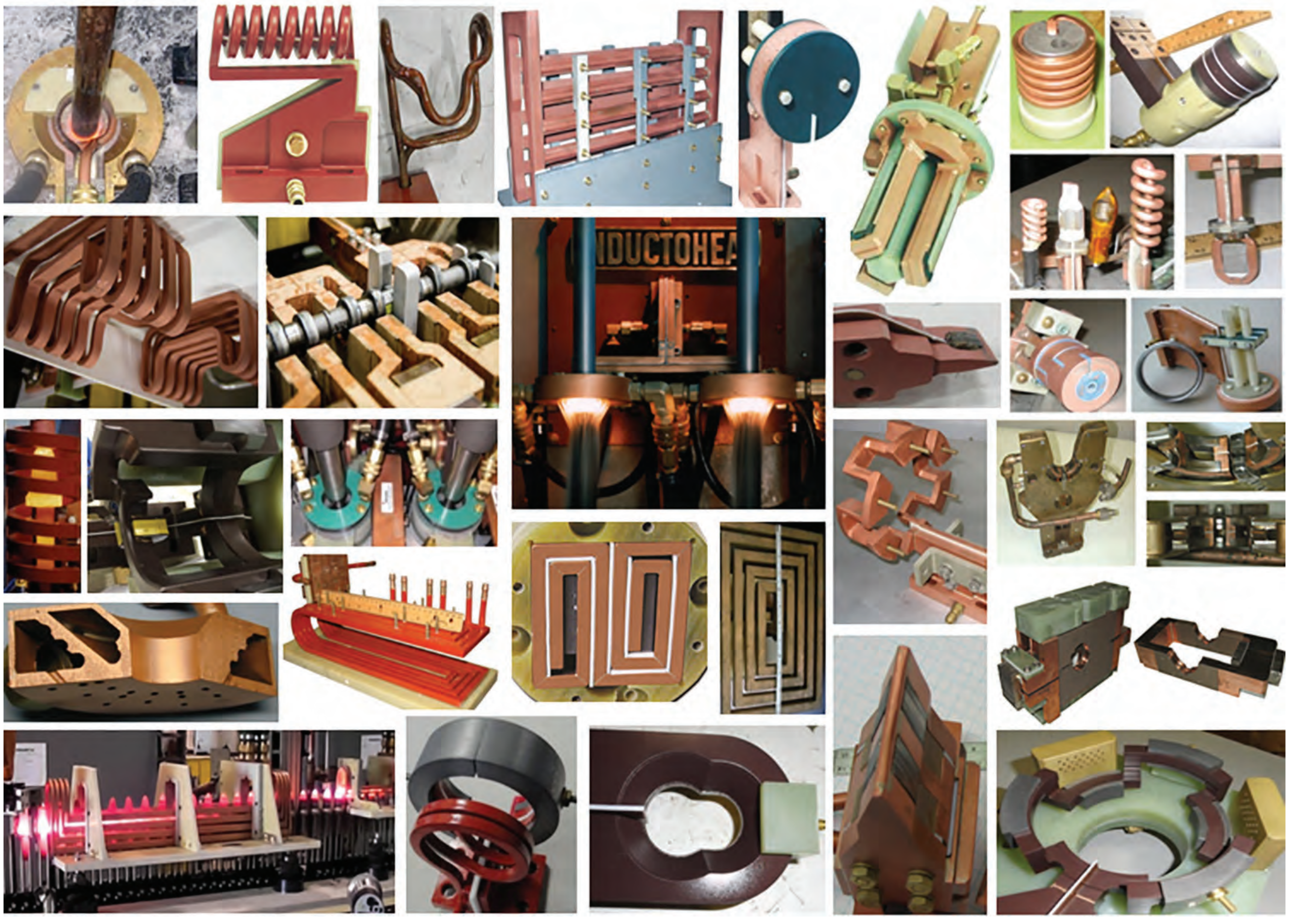

Fig. 1 — Array of different induction coil designs.

spatial relationships, which produce inductors of the required shape and precision. Figure 2 shows a variety of finished and semifinished CNC-machined hardening inductors. In the past, most of these inductors were fabricated by brazing and banding coils. CNC machining is a superior method to achieve accurate, robust inductors for use in automotive, aerospace, defense and other industries where high process repeatability is critical.

Brazing is completely eliminated with some CNC-machined inductors, such as those used in Inductoheat's nonrotational SHarP-C processes for hardening crankshafts and camshafts. Brazing is minimized in other applications, used only to encapsulate water-cooling channels.

Some inductors, especially those used in selective hardening, have very complex geometries. A computerized 3D metrology laser scanner is used to verify coil dimensional accuracy and alignment precision within about 25 microns (0.001 in.) after fabrication and assembly (Fig. 3).

CONVENTIONAL INDUCTORS

Steel shafts and shaft-like components are among parts that traditionally are induction hardened using scanning or single-shot heat treating. With the single-shot method, neither the shaft nor coil move relative to each other; the part typically rotates instead. The entire region to be hardened is heated at the same time.

A single-shot inductor consists of two legs and two crossover segments, also known as bridges or horseshoe half-loops (Fig. 4). Crossover segments encircle only half of the workpiece circumference, and induced eddy currents primarily flow along the length of the part. An exception is crossover segments where the flow of eddy current is half circumferential. Longitudinal leg sections are profiled by relieving selected regions of the copper to accommodate workpiece geometrical features, such as changes in diameter or irregularities. Section(s) of a single-shot inductor with narrower heating surfaces facing the shaft increase induced power density in desirable regions(s).

For a workpiece containing fillets, it is often necessary to increase heat intensity in the fillet region to heat the greater volume of metal. Also, the larger metal mass in the proximity of the heated fillet and behind the region to be hardened produces a substantial "cold sink" effect. This draws heat from the fillet due to thermal conduction, which must be compensated for by inducing additional heating energy in

Fig. 2 — Variety of finished and semifinished CNC-machined hardening induction coils.

the fillet area. The required energy surplus can be achieved by narrowing the current carrying face of the appropriate section of the single-shot inductor. For example, if the current carrying portion of the inductor heating face is reduced by 50%, there is a corresponding increase in current density, as well as the eddy current density induced within the respective shaft region. According to the Joule effect, doubling the induced eddy current density increases induced power density by a factor of four. Also, attaching a magnetic flux concentrator to certain areas of the hardening inductor (Fig. 4) further enhances localized heat intensity.

The effects of intensifying heat generation in selected areas of the shaft (i.e., excessive current densities in inductor sections combined with intense heat radiation from the workpiece surface) can cause localized copper overheating. This promotes water vaporization and the formation of a steam vapor barrier, which essentially functions as a thermal insulator inside the water-cooling pocket. Thus, copper cooling is severely restricted even when it appears that there is sufficient water-cooling flow and regardless of the use of high-performance pumps. To help prevent overheating, water-cooling pockets are placed as close as possible to the current carrying face of an inductor. However, coil overheating can still occur and cause accelerated deterioration of the copper surface, which speeds up the onset of inductor copper cracking (due to stress fatigue and stress corrosion, for example) and eventual premature coil failure. As a result, coil life is often shortened to 22,000-24,000 heat cycles (industry average). Therefore, the number of instances where coil current density is increased should be kept to a minimum.

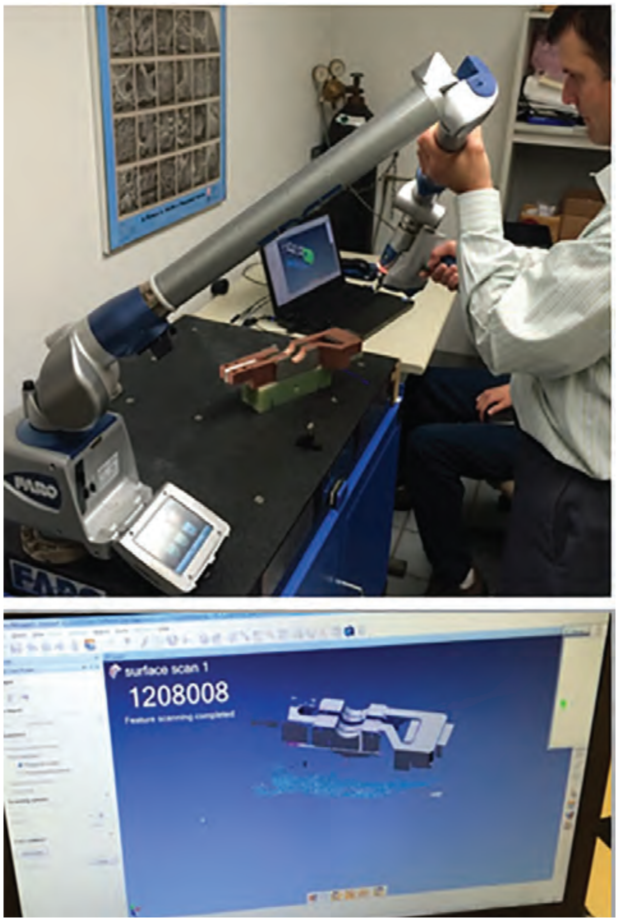

Fig. 3 — A computerized 3D metrology laser scanner is used to evaluate fabricated coils to ensure geometrical accuracy and alignment, storing measurement data for inductor certification.

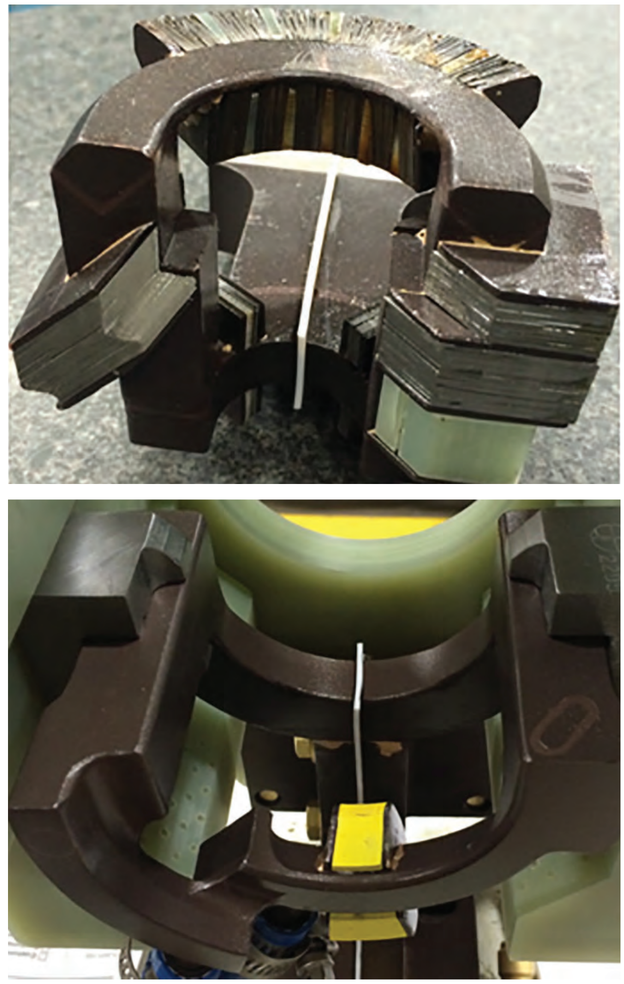

Fig. 4 — A magnetic flux concentrator is attached to certain areas of the hardening inductor coil to enhance localized heat intensity.

Conventionally fabricated single-shot inductors exhibit high process sensitivity, which has a negative effect on the repeatability of part heating and the quality of hardened components. High sensitivity is associated with an electromagnetic proximity effect. A change in positioning of the shaft inside the single-shot inductor due to bearing wear, incorrect part loading in the inductor, and other factors produces an immediate variation of heating intensity, particularly within the fillet region. This results in a local heat deficit and therefore reduced hardness depth.

INDUCTOR BREAKTHROUGH

Inductoheat recently developed a new inductor design (patent pending) that dramatically reduces localized coil current density in areas prone to overheating and cracking (Fig.5). The presence of a two-collar section reduces coil current by one half, which dramatically reduces localized heat generation in the copper and significantly extends coil life.

In addition, for a shaft positioned asymmetrically within the inductor, there is a reduced heating effect produced in one of the two half-collar sections that has an increased

Fig. 5 — Novel inductor design (patent pending) dramatically extends coil life in single-shot hardening of complex shaft-like components.

inductor-to-shaft gap. This is offset by an increased induced heating effect produced in the other half-collar section that has a reduced inductor-to-shaft gap. Consequently, process sensitivity associated with positioning the shaft within the inductor is reduced over that with a conventionally designed single-shot inductor.

In one application of the new inductor, one of the world's largest suppliers of automotive parts achieved a nine-fold increase in a single-shot coil life compared with that for conventional inductors. This is verified by the manufacturer's tool-room tag showing that the inductor (which the customer named "magic coil") was still considered in good shape after 225,000 heat cycles (Fig. 6). Other benefits include measurable improvement in process robustness, coil reliability, and maintainability.

Portions of this article are adapted from the chapter "Systematic Analysis of Induction Coil Failures and Prevention" in *Induction Heating and Heat Treating*, Vol 4C, *ASM Handbook*, V. Rudnev and G. Totten (Editors), ASM International, 2014.

Coil design details and benefits will be presented in a paper at Heat Treat 2015, taking place October 20-22 at Cobo Convention Center in Detroit.

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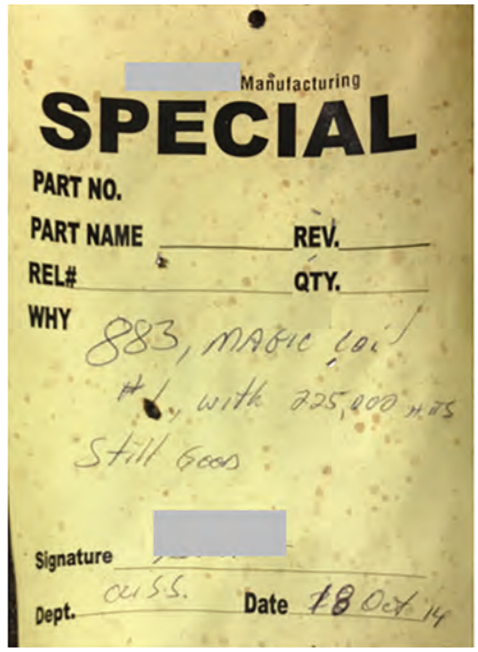

Fig. 6 — Automotive component manufacturer's tool-room tag indicates that Inductoheat's newly designed inductor is still considered in good shape after 225,000 heat cycles, a nine-fold increase in single-shot coil life compared with that for conventionally designed inductors.