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Systematic analysis of induction coil failures

PART 3: COIL COPPER SELECTION

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 and 2 appeared in the August and September/October issues, respectively.

Induction coils for hardening applications are typically CNC machined from a solid copper bar, thus making them rigid, durable, and repeatable; in certain other cases, a copper tube (rectangular or round) may be used for coil fabrication. As discussed in References 1 and 2, copper is used for coil fabrication instead of other metals because of its unique properties that include, but are not limited to, good electrical and thermal conductivities, inherent corrosion resistance, and superior cold and hot workability. Copper's availability and its mechanical properties and cost are other important factors that make the metal an excellent choice for coil fabrication. Various copper alloys are used.

Space limitations prevent a detailed discussion of all the properties of copper alloys and their effect on coil life. Only selected properties will be discussed here.

Key Electrical Properties

The electrical conductivity of copper, σ_{Cu}, is an important physical property that dramatically affects the life of the induction coil. The electrical conductivity of a material is a measure of how easily it conducts electric current. The reciprocal of σ_{Cu} is electrical resistivity, ρ_{Cu}. The units for σ_{Cu} and ρ_{Cu} are mho/m and Ω•m, respectively. Electrical conductivity of a particular copper grade can also be expressed in comparison to a volume conductivity of 100% of the International Annealed Copper Standard, written 100% IACS.[3] Both σ_{Cu} and ρ_{Cu} can be used in engineering practice; however, most engineering data books contain primarily electrical resistivity data. Therefore, the value of ρ_{Cu} will be used here.

Electrical resistivity varies with temperature, chemical composition, metal structure, and grain size, and depends strongly on purity. Phosphorus, tin, selenium, tellurium, and arsenic are some of the typical impurities found in commercially pure copper. Impurities distort the copper lattice, affecting ρ_{Cu} to a considerable extent. For example, Fig. 1 shows an increase in ρ_{Cu} of copper with admixtures of various elements.[3, 4] Figure 2 shows the change in electrical resistivity of high-purity copper with the addition of secondary elements in solid solution.[3, 5] Note that even relatively small amounts of impurities or trace elements, including oxygen (which oxidizes copper), can appreciably increase copper's electrical resistivity, leading to a corresponding increase in coil electrical resistance and Joule losses dissipated within the inductor.

In addition, as for most metals, ρ_{Cu} rises with temperature. Therefore, unexpected heat dissipation within the copper will cause a further increase in coil electrical resistance.

Effects on failure: All these factors lead to a reduction in coil electrical ef-

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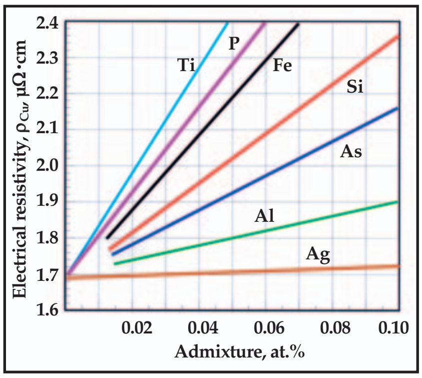

Fig. 1 — Increase in the electricity resistivity, ρ_{Cu}, of oxygen-free copper with admixtures of various elements. Source: Ref 3, 4.

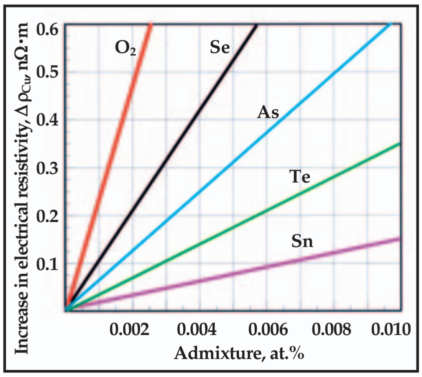

Fig. 2 — The change in electricity resistivity, ρ_{Cu}, of high-purity copper with the addition of various elements in solid solution. Source: Ref 3, 5.

ficiency, requiring higher coil current and power in order to induce the same power in the heated workpiece. Higher coil current creates favorable conditions for the appearance of localized "hot" spots and appreciably increases the growth rate of a crack in the coil copper.[6]

Although alloying copper can noticeably improve certain mechanical properties and corrosion resistance, it also reduces the material's thermal conductivity. This decreases the capability of water-cooled passages to reduce the localized overheating caused by the less intensive heat removal due to diminished thermal conduction.

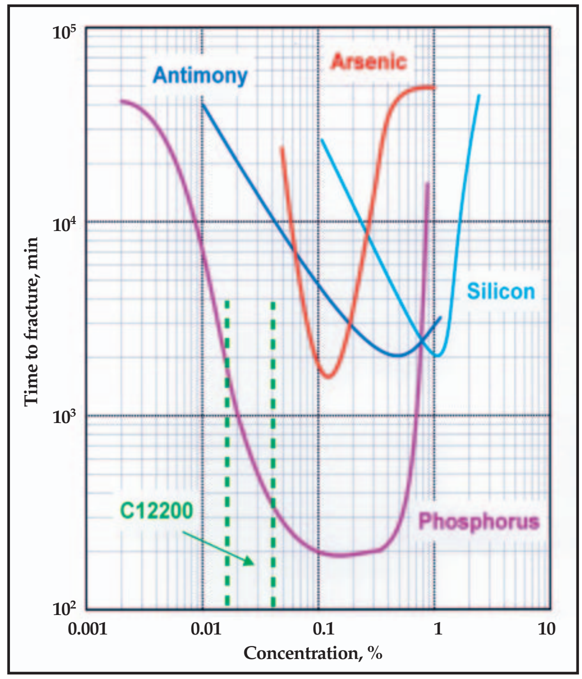

Fig. 3 — Effect of the presence of low concentrations of alloying elements on time to fracture of copper by stress-corrosion cracking under an applied tensile stress of 70 MPa (10 ksi) in a moist atmosphere. UNS C12200 is a wrought phosphorus deoxidized copper. Source: Ref 6.

Stress-corrosion cracking, stress-fatigue cracking, galvanic corrosion, and some other important phenomena that have a marked effect on coil failure are affected by residual elements and alloying elements. For example, Fig. 3 shows the effect of low concentrations of some elements on time-to-fracture of copper by stress-corrosion cracking under an applied tensile stress of 70 MPa (10 ksi).[7] Water pH is yet another factor that has an appreciable effect on copper susceptibility to cracking.

Next: Coil Copper Edge Effect

Nonuniform coil current distribution resulting from various electromagnetic phenomena has dramatic effects on crack development. Some of those phenomena were discussed in Part 2 of this series.[2] Part 4 will focus on how the electromagnetic edge effect influences copper cracking and coil life.

When all factors are considered, successful coil copper selection hinges on arriving at a reasonable compromise among copper's electrical properties, thermal properties, mechanical properties, and cost.

References

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