PROFESSOR INDUCTION

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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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Systematic analysis of induction coil failures

PART 11b: FREQUENCY SELECTION

Entries in the "Systematic analysis of induction coil failures" series alternate with those in the new "Metallurgical insights for induction heat treaters" series, which made its debut in the May/June 2007 HTP.

It has been said, and too often quoted, that the only certainties in life are death and taxes. The user of induction heating could add a third: the certainty of being confused about which frequency is best suited to a particular induction heating or induction heat treating application. The July column discussed an effect of temperature on electrical resistivity (ρ) of pure metals, frequency selection, coil copper losses, and coil life.[1]

Besides temperature, the value of electrical resistivity is affected by grain size (higher ρ corresponds to finer grains), plastic deformation, heat treatment, chemical composition, and other factors.

It has also been shown that an increase in ρ with temperature must be taken into account when selecting the most suitable operating frequency, and the electrical resistivity of pure metals can often be represented as a linear function of temperature.[2]

If operating frequency is chosen based on the value of ρ at ambient temperature, then the increase in electrical resistivity with temperature could potentially have a detrimental effect on coil efficiency and coil-cooling requirements due to eddy current cancellation and a dramatic increase in copper losses. Underestimation of that effect can result in overheating and a shortening of coil life.

Unfortunately, we very seldom deal with pure metals in real-world applications. All commercial grades of metals typically contain certain amounts of other chemical elements.[2] Some of these additional elements are present in trace amounts as residual impurities from raw materials, while others were intentionally added to produce certain properties. The effect of additional chemical elements on induction heating and the selection of critical process parameters such as power and cooling requirements, inductor copper losses, and frequency selection can be dramatic. Potential errors can exceed 10-fold, severely affecting inductor longevity and unpleasantly surprising professionals. Unfortunately, this effect has never been addressed in induction heating publications. This column intends to bridge this gap.

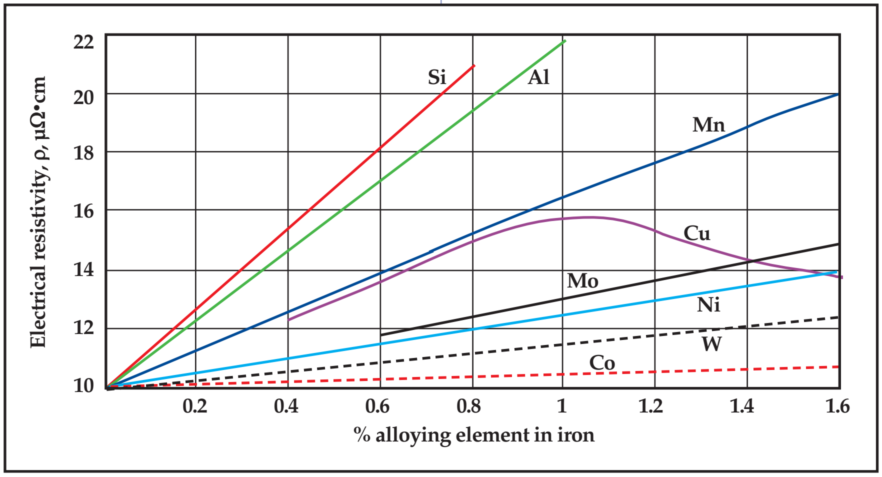

Fig. 1 — Dependence of electrical resistivity, ρ, on the addition of small amounts of various alloying elements to iron. (Ref. 3)

How added elements affect ρ

Impurities in metals distort the crystal lattice and can affect the behavior of ρ to a considerable extent. This is particularly true for metal alloys.[3–6] The effects of various elements on the electrical resistivity of alloys are different and depend on the types of phases they constitute.

Unfortunately, developers of induction heating processes often in-

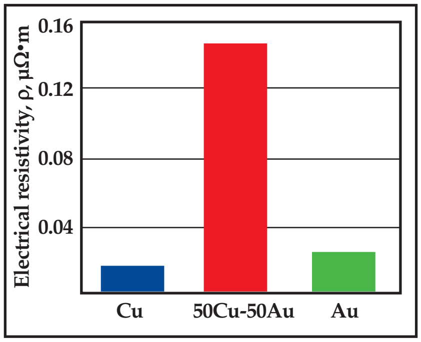

Fig. 2 — Electrical resistivity, ρ, vs. percentage of alloying element in a Cu-Au binary alloy. (Ref. 4)

correctly assume that certain physical properties of a binary alloy can be approximated as an average value of two extremes. In reality, however, electrical resistivity may continuously decrease or increase with concentration of the alloying elements. For example, the electrical resistivity of plain carbon steels increases with an increase in the carbon content and some other alloying elements. This is demonstrated in Fig. 1 for various alloying elements in iron. But in other cases, particularly those that form solid solutions, this dependence is appreciably nonlinear. Also, many are unaware that in still other cases, the behavior of ρ vs. the alloying element concentration can be represented by a "bell-shaped curve." This curve typically has its maximum electrical resistivity value at a concentration of alloying elements equal to 50% of the atomic weight.[4–6] Figures 2 and 3 illustrate this phenomenon.

Why averaging ρ is dangerous

The danger in using an average value for electrical resistivity while induction heating binary alloys is dramatized in an example involving Cu-Ni alloys (dotted line, Fig. 3). A 6.4 mm (0.25 in.) in diameter 50Cu-50Ni alloy rod is to be heated from ambient temperature to 200°C (390°F).

Table 1 shows eddy current penetration depths for pure copper, pure nickel, and, for 50Cu-50Ni, using an average value of the two extremes (the

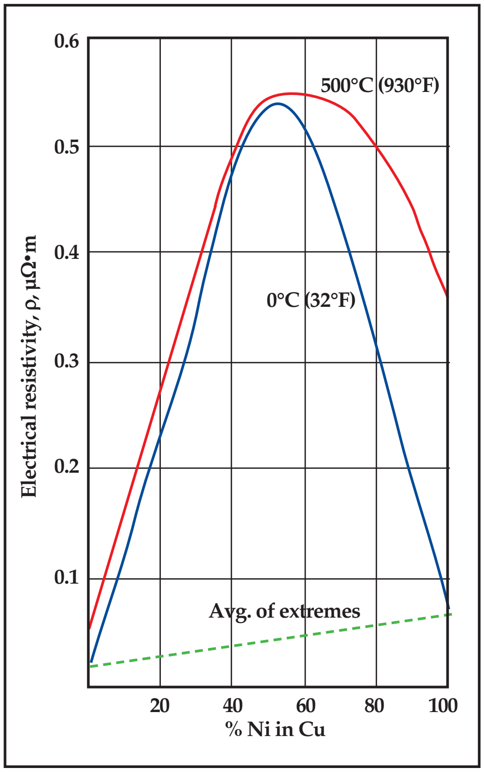

Fig. 3 — Electrical resistivity, ρ, of Cu-Ni alloys at different temperatures. (Ref. 6)

incorrect assumption) and a "bell-shaped curve" (correct value). Data are at frequencies of 3 and 6 kHz.

Table 2 shows the *minimal* frequencies for efficient heating of 6.4 mm (0.25 in.) in diameter 50Cu-50Ni rod, avoiding eddy current cancellation within the rod. Using the average value of electrical resistivity, ρ — the incorrect assumption — can result in substantially misleading recommendations for process frequency (more than 10-fold) that, in turn, can lead to a dramatic reduction in coil efficiency and premature coil failure due to unexpected excessive coil copper losses. In fact, under certain conditions a workpiece (rod, bar, billet, or wire, for example) could start to become transparent to the electromagnetic field and its heating would not be practically possible regardless of applied coil power.

Two primary conclusions

- Although variations in electrical resistivity have virtually no effect on heating of alloys in fuel-fired furnaces, infrared heaters, fluidized bed furnaces, or salt baths, they do have a dramatic effect on induction heating and the selection of major process parameters such as operating frequency.
- An inaccurate assessment of the electrical properties of heated alloys can dramatically reduce heating efficiency, which, in turn, could lead to unexpected excessive copper losses, greater magnetic forces experienced by the coil, and, as a result, potential shortening of coil life.[1,7] In some cases, eddy current cancellation can be so pronounced that it will be practically impossible to heat the workpiece, regardless of applied coil power, unless the frequency is changed.

Table 1 — Eddy current penetration depth vs. frequency and material at ambient temperature

Material at 0°C (32°F)	Penetration depth, mm (in.)		Comments
	3 kHz	6 kHz	
Pure copper	1.2 (0.05)	0.85 (0.03)	—
Pure nickel	2.34 (0.09)	1.65 (0.065)	—
50Cu-50Ni	1.9 (0.075)	1.3 (0.05)	Using an average value of ρ (incorrect assumption)
50Cu-50Ni	6.62 (0.26)	4.7 (0.185)	Using the correct value of ρ

Table 2 — Minimal frequency, kHz, for efficient heating of 6.4 mm (0.25 in.) in diameter rod at 0°C (32°F)

Pure copper	Pure nickel	50Cu-50Ni (incorrect assumption used for ρ)	50Cu-50-Ni (using the correct value of ρ)
1.5	5.2	3.3	42

References

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