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# Systematic analysis of induction coil failures

## PART 11a: 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* 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.

Frequency selection not only affects the performance of the induction system but it also has a significant effect on coil life. Choice of an improper frequency is the most common mistake made by developers and users of induction heating processes.

Numerous factors affecting frequency selection for surface (case) hardening, tempering, and stress relieving are discussed in Ref. 1. Frequency selection and the detrimental effect on coil life of choosing an improper frequency for induction through-heating applications (including through hardening, annealing, normalizing, and heating prior to hot and warm forming, for example) is the topic of this column and two others in the "Systematic analysis of induction coil failures" series.

### Electromagnetic properties

Unlike fuel-fired and infrared furnaces, the performance of induction heaters first and foremost is affected by the electromagnetic properties of the heated metal.[1]

Electromagnetic properties of materials encompass a variety of characteristics including magnetic permeability, electrical resistivity (electrical conductivity), saturation flux density, coercive force, hysteresis loss, permittivity, and many others.[2] While recognizing the importance of all electromagnetic properties, two of them — electrical resistivity (electrical conductivity) and magnetic permeability — have the most pronounced effect

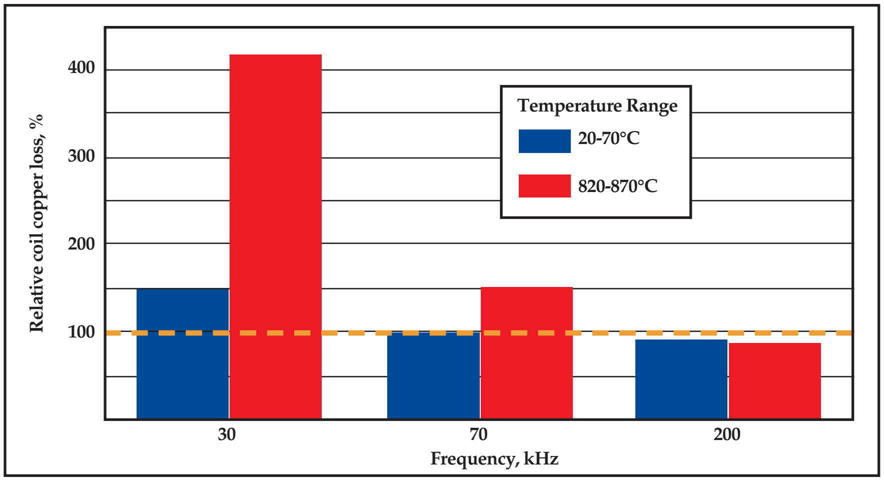

*Fig. 1 — Relative coil copper losses at initial heating stage (20 to 70°C [70 to 160°F]) compared with those at the final heating stage (820 to 870°C [1510 to 1600°F]) while induction heating 0.25 in. (6.4 mm) in diameter titanium rod using a frequency of 70 kHz versus 30 and 200 kHz, assuming the same rise of average temperature per heat time. As the reference point, coil copper losses at the initial heat stage using 70 kHz are assigned a value of 100%.*

on the performance of an induction heating system, its efficiency, longevity, and frequency selection.

### Resistivity (conductivity)

The ability of a material to conduct an electric current is indicated by its electrical conductivity, $\sigma$.[2] The reciprocal of conductivity is electrical resistivity, $\rho$. The units for $\rho$ and $\sigma$ are $\Omega$·m and mho/m, respectively. Both characteristics can be used in engineering practice; however, the majority of data books contain values for electrical resistivity.

Electrical resistivity of a particular metal varies with temperature, chemical composition, microstructure, and grain size. Metals considered to be low resistivity include silver, copper, gold, and aluminum, while high-resistivity metals include stainless steel, titanium, and carbon steel. For most metals, $\rho$ rises with temperature.

The resistivity of pure metals can often be represented as a linear function of the temperature (unless there is a change in the metal's lattice structure):

$$\rho(T) = \rho_o[1 + \alpha(T - T_o)] \qquad \text{(Eq. 1)}$$

where $\rho_o$ is the resistivity at ambient temperature, $T_o$; $\rho(T)$ is the resistivity at temperature $T$; $\alpha$ is the temperature coefficient of the electrical resistivity (in units of 1/°C).

For some electrically conductive materials, electrical resistivity decreases with temperature and, therefore, the value of $\alpha$ can be negative. For other materials (including carbon steels, alloy steels, and graphite, for example) $\alpha$ is a nonlinear function of temperature due to a nonlinear function of $\rho$ vs. temperature.

Do not confuse electrical resistivity, $\rho$ (in $\Omega$·m) with electrical resistance, $R$ (in $\Omega$). The relationship between these parameters can be expressed as:

$$R = \rho l/a \qquad \text{(Eq. 2)}$$

where $l$ is the length of the current-carrying conductor and $a$ is the area of the conductor's cross section through which the current is flowing.

*Table 1 — Examples of how electrical resistivity, $\rho$, rises with temperature*

| Material | Increase in electrical resistivity, x | Temperature range, °C (°F) |
|---|---|---|
| Aluminum | 3.2 | 21 → 500 (70 → 932) |
| Copper | 4.7 | 21 → 900 (70 → 1652) |
| Titanium | 3.15 | 21 → 885 (70 → 1625) |
| AISI 1045 steel | 6.8 | 21 → 1200 (70 → 2192) |
| Tungsten | 10.6 | 21 → 1800 (70 → 3272) |

Electrical resistivity affects practically all of the important parameters of an induction heating system, including depth of heating, coil electrical efficiency, coil losses, and water cooling requirements, among others.

### Effect of frequency

In the case of induction through-heating of solid cylinders (rods, bars, billets, and wires, for example), there will be higher coil efficiency when the applied frequency corresponds to this ratio:

$$\text{(Workpiece diameter, } D\text{)/(Current penetration depth, } \delta\text{)} > 4 \qquad \text{(Eq. 3)}$$

In metric (SI) units, current penetration depth, $\delta$, can be calculated as:

$$\delta = 503(\rho/\mu_r F)^{1/2} \qquad \text{(Eq. 4a)}$$

where $\rho$ is the electrical resistivity of the metal, $\Omega$·m; $\mu_r$ is the relative magnetic permeability (1 for nonmagnetic materials); and $F$ is the frequency, Hz (cycles per second).

In English units,

$$\delta = 3160(\rho/\mu_r F)^{1/2} \qquad \text{(Eq. 4b)}$$

where electrical resistivity $\rho$ is in $\Omega$·in.

If the ratio $D/\delta$ is $< 3$, than coil electrical efficiency dramatically decreases due to the cancellation of induced eddy currents circulating in opposite sides of the heated workpiece.[1] This reduction in coil efficiency causes a corresponding increase in coil copper losses and necessitates having appreciably greater coil water-cooling. If water cooling isn't sufficiently increased, premature coil failure could result due to copper overheating and degradation.

Eddy current cancellation and the attendant dramatic reduction in coil efficiency and increase in coil copper losses are responsible for a phenomenon that sometimes puzzles induction heating users: A coil can last longer when heating larger-diameter parts, but fail prematurely when it's used to heat small-diameter workpieces. The power supply is the same in both cases.

An example is given in Fig. 1 (blue bars), which shows the *relative* variation of coil copper losses at the initial heating stage (20 to 70°C [70 to 160°F]) when induction heating 0.25 in. (6.4 mm) in diameter titanium rod using a frequency of 70 kHz versus 30 and 200 kHz, assuming the same rise of average temperature per heat time. As the reference point, coil copper losses at 70 kHz are designated as 100%.

### Effect of temperature

As discussed, the electrical resistivity, $\rho$, rises with temperature for most metals. This increase can be appreciable resulting in the potential for a dangerous current cancellation at the final heating stage.

Table 1 shows the increases in electrical resistivity for several metals for typical heat temperatures.

It is imperative to take into account an increase in electrical resistivity with temperature when selecting the most suitable operating frequency. Unfortunately, most data sources only have information regarding the value of electrical resistivity at ambient temperature. If the $D/\delta$ ratio (Eq. 3) is chosen based on the value of electrical resistivity at ambient temperature, then the increase in electrical resistivity with temperature could potentially have a detrimental negative effect on coil efficiency and copper cooling requirements. Underestimation of that effect can result in overheating and a noticeable shortening of induction coil life.

Figure 1 also compares relative coil copper losses at the initial heating stage with those at the final heating stage (820 to 870°C [1510 to 1600°F]) while induction heating titanium rod using three frequencies.

## Conclusions drawn

- Premature coil failure that results from unexpected excessive coil losses can be avoided by selecting an operating frequency that avoids eddy current cancellation.
- To ensure high heating efficiency and long coil life, frequency should be chosen based on current penetration depth at the end of heating (final heating stage).

## Author comments

The ability to independently change the frequency and/or power of an induction heating system would enhance process flexibility, and has been on the wish list of commercial induction heat treaters for some time. Inductoheat's Statitron IFP (Independent control of Frequency and Power) inverter does just that, allowing the independent changing of frequency (over a 5 to 40 kHz range) and power (over a 10 to 75 kW range) in a single-module system. Heat treaters can now program power and/or frequency changes on the fly, which greatly expands equipment capabilities for processing parts, maximizing heating efficiency while treating different part sizes and/or optimizing the performance of both hardening and tempering while using the same power supply.

## 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. *Ferromagnetism*, by Richard M. Bozorth: IEEE Press, New York, 1993 (as a "Classic Reissue"), 968 p.