Systematic analysis of induction coil failures

PART 11c: FREQUENCY SELECTION

Entries in the “Systematic analysis of induction coil failures” series alternate with those in the “Metallurgical insights for induction heat treaters” series.

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, and many others. While recognizing the importance of all electromagnetic properties, two of them — electrical resistivity (electrical conductivity) and magnetic permeability — have the most pronounced effect on the performance of an induction heating system, its efficiency and longevity, and frequency selection.

The July and September/October 2007 columns discussed an effect of electrical resistivity (ρ) of pure metals and alloys on frequency selection, copper losses, and coil longevity.²,³ Inappropriate selection of operating frequency could potentially have a detrimental effect on coil efficiency and its cooling requirements due to eddy current cancellation and a dramatic increase in copper losses. Underestimation of that effect can result in overheating and compromising the service life of the induction coil. This column discusses an effect of magnetic permeability on frequency selection and coil copper losses.

Magnetic Permeability

Relative magnetic permeability, μr, indicates the ability of a material (a metal in this case) to conduct a magnetic flux better than vacuum or air. The constant μ₀ = 4π x 10⁻⁷ H/m [or Wb/(A·m)] is called the permeability of free space (a vacuum). The product of relative magnetic permeability and the permeability of free space is called magnetic permeability, μ, and corresponds to the ratio of the magnetic flux density (B) to the magnetic field intensity (H).

\[ \frac{B}{H} = \mu_0 \mu = \mu, \text{ or } B = \mu_0 \mu H = \mu H \]

In everyday engineering language, induction heating specialists often call the relative magnetic permeability simply magnetic permeability.

All materials based on their magnetization ability can be divided into paramagnetic, diamagnetic, and ferromagnetic. Relative magnetic permeability of paramagnetic materials is slightly greater than 1 (μr > 1). The value of μr for diamagnetic materials is slightly less than 1 (μr < 1). Due to insignificant differences between μr for paramagnetic and diamagnetic materials, they are simply called nonmagnetic materials in induction heating practice. Typical nonmagnetic metals are aluminum, copper, titanium, and tungsten.

Ferromagnetism: In contrast to paramagnetic and diamagnetic materials, ferromagnetic materials exhibit high values of relative magnetic permeability (μr >> 1). There are only a few elements that exhibit ferromagnetic properties at room temperature; among them are iron, cobalt, and nickel.

A material’s ferromagnetic property is a complex function of structure, chemical composition, frequency, magnetic field intensity, and temperature. As shown in Fig. 1a, the same kind of carbon steel at the same temperature and frequency can have a different value of μr due
Temperature, $T$ [10 to 750ºC (50 to 1382ºF)].

The temperature at which a ferromagnetic body becomes nonmagnetic is called the Curie temperature (Curie point). The Curie temperatures of some magnetic materials are shown in Table 1.

Depending upon the heat intensity (ºC/s or ºF/s) there can be some shifting of the Curie temperature. Chemical composition is another factor that has a marked effect on it. Even among the plain carbon steels, the Curie temperature might be different due to the carbon content, as shown in Fig. 1b. The Curie point of a plain carbon steel is called the A₂ critical temperature. For an example of the effect of carbon content, compare the Curie temperature of AISI 1008 carbon steel with that of AISI 1060 in Table 1.

Figure 2 is a dramatic illustration of the complex relationship among μᵣ, temperature, and magnetic field intensity for a medium carbon steel.

Figures 1 and 2 imply that magnetic permeability always decreases with increasing temperature. This is indeed the case in the majority of induction heat treating applications. However, in a relatively “weak” magnetic field, μᵣ might first increase with temperature and only near the Curie point would it begin to drastically decline.¹

Penetration Depth, Efficiency

In discussions of induction heating, reference is often made to the skin effect — eddy currents induced within the heated workpiece primarily flow in the surface layer, or “skin,” where 86% of all induced power will be concentrated.¹² The thickness of this layer is called the reference depth or current penetration depth, δ. The value of penetration depth varies with the square root of electrical resistivity and inversely with the square root of frequency and the relative magnetic permeability of the workpiece.¹²

Current penetration depth is one of the other factors that affect coil efficiency and coil copper losses. Heating is said to be efficient when the ratio of cylinder diameter to δ is > 4. If diameter/δ < 3, coil efficiency will dramatically decrease. This is due to the cancellation of induced eddy currents circulating in opposite sides of the heated cylinder.

There are several unique aspects of induction heating magnetic materials such as carbon steel rods or bars, compared with heating nonmagnetic metals. At the initial heating stage, the cylinder is magnetic, δ is small, and coil efficiency is high (typically at least 80%). Current penetration depth into the carbon steel initially increases slightly with temperature because of the rise in the metal’s electrical resistivity. However, when the temperature exceeds about 550ºC (1022ºF), magnetic permeability begins to noticeably decline (Fig. 1a), which results in a marked increase in current penetration depth.

Since near the A₂ critical temperature (the Curie point), permeability plummets to unity because the metal becomes nonmagnetic, the current penetration depth increases significantly (by a factor of 15 or more), which could lead to eddy current cancellation within the heated workpiece and a large reduction in coil efficiency. The decrease in coil efficiency causes an increase in coil copper losses, which necessitates having substantially greater coil water-cooling. If water cooling isn’t sufficiently increased, premature coil failure could result due to copper overheating and degradation. Therefore, when selecting frequency it is imperative to evaluate whether eddy current cancellation might take place.

Dual-Frequency Case Study

A dual-frequency design concept can be beneficial. In this technique, a low
frequency is used during the initial heating stage, when the steel is magnetic. In the final heating stage, when the cylinder becomes nonmagnetic, it is more efficient to use a higher frequency. As an example, consider the induction heating of a 3.18 mm (1/8 in.) in diameter carbon steel rod from ambient temperature to 1120°C (2050°F) using both a single 10 kHz frequency and dual 10 kHz/200 kHz frequencies (Fig. 3).

As shown in Fig. 3a, for the single 10 kHz frequency, the final temperature of the rod experiences very little change when coil power is increased more than five-fold (from 17 kW to 90 kW). The only noticeable difference is the slope of the temperature vs. time curve. This change occurs during the first stage of heating when the steel is magnetic. Then, when the steel reaches the Curie temperature, there is no noticeable temperature rise. This is the result of eddy current cancellation when the temperature exceeds the Curie point. (Power difference represents additional coil copper loss.)

In contrast, Fig. 3b shows that a dual-frequency approach provides a remarkable improvement in the ability to heat the rod above the Curie temperature. A power of 14 kW/10 kHz was used to heat the rod below the Curie point and a power of 19 kW/200 kHz was used above the Curie temperature. The total required power is 33 kW, compared with 90 kW using the single, 10 kHz frequency, which was unable to provide the required temperature rise.

This case study stresses the importance of avoiding current cancellation when choosing an operating frequency. It is often required that the induction system should be able to heat a variety of sizes using a single frequency. In these cases, in order to provide efficient heating and reduce copper losses, it is necessary to choose a frequency that will guarantee that the diameter/δ ratio will exceed 3.4 for any workpiece size or stage of heating.

A final note: It is important to remember that when calculating current penetration depth, the values of electrical resistivity and relative magnetic permeability of the metal should correspond to their values at the highest temperature that occurs during the heating process.

**Correction**

In the Professor Induction column in the November/December issue of Heat Treating Progress, Figure 3 (p 24) is not sized proportionally, which changed the shape and wall thickness of the inductor (it should be square, instead of rectangular, with uniform wall thickness) and distorted the heat-sink effect. The correct shape and heat-sink effect are shown in the accompanying figure. We apologize for any inconvenience this may have caused.

**References**

