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Metallurgical insights for induction heat treaters

PART 6: STRIPING PHENOMENON

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

Heat-treat practitioners sometimes observe unusual effects in induction hardening, such as a striping phenomenon, a barber-pole effect, and a snakeskin effect. The appearance of a striping phenomenon is discussed in this article[1]. The barber-pole effect and snake-skin effect will be discussed in Part 7 of Metallurgical insights for induction heat treaters.

Type A Striping Phenomenon

The striping phenomenon appears when a single-shot or static heat mode is used. Two types of striping phenomenon in induction hardening: Type A and Type B[1]. Although the appearance of both types is similar, the physics behind each is quite different.

The Type A striping phenomenon appears when a multi-turn coil is used, and can be observed when heating both ferrous and nonferrous metals, particularly those that have relatively poor thermal conductivity. An undesirable combination of small inductor-to-workpiece gaps, relatively high power densities, short heat times, and loosely wound coil turns might result in an uneven stripe-type temperature distribution along the length of the workpiece. Stripes are caused by localized power surpluses due to electromagnetic coupling between particular coil turns and located in the close proximity workpiece areas. The number of stripes is directly related to the number of coil turns. If heat time is sufficiently long, thermal conductivity of heated metal equalizes temperatures of the workpiece areas with different induced power densities (heat sources). Proper coil design, selection of process parameters and rotation of heated workpiece can eliminate this undesirable phenomenon.

Type B Striping Phenomenon

Type B striping phenomenon (Fig. 1) occurs only during intensive induction heating of ferrous alloys, including carbon steels and cast irons where short

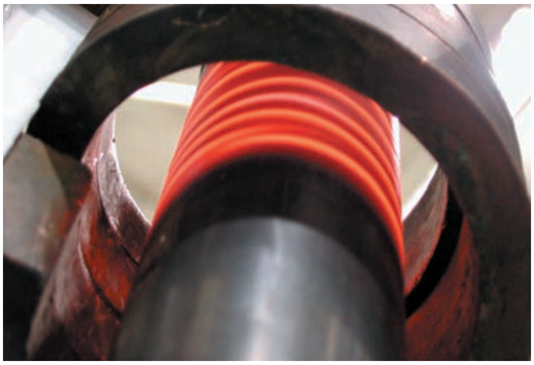


Fig. 1 — Multiple stripes appear due to a striping phenomenon. (Note that the induction coil has only four turns.)

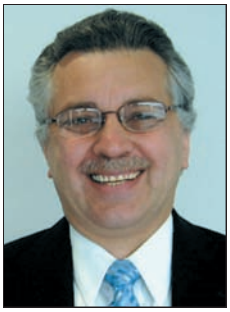
heat up times and high power densities are used. Multiple stripes can be observed by the naked eye on the surface of a heated cylinder even in the case when a single-turn induction coil is used.

Due to Type B striping, the workpiece area under the coil may unexpectedly start to heat nonuniformly (Fig. 1). Shortly after the heating cycle begins, alternating hot bright areas (bright stripes) and cold areas (dark stripes) become visible. These bright and dark stripes encircle the cylinder, and, thus, have a ring shape. The number of rings is not necessarily related to the number of coil turns.

Type B striping has never been obtained by computer modeling. It has been viewed only in practical applications or in laboratory experiments during the induction heating of magnetic metals, and is considered a mysterious phenomenon. In some applications, striping suddenly occurs and then disappears. There is no single explanation of this phenomenon. M. Lozinskii attempted to explain it in the 1960s[2].

Assume that a magnetic cylinder is located inside a cylindrical inductor. As a result of the electromagnetic field produced by the induction coil, eddy currents will flow within the workpiece. Due to the skin effect, these eddy currents appear primarily in the surface layer of the cylinder located inside the coil and cause an increase of its surface temperature.

In reality, any metal has certain non-uniformities, micro and macroscopic defects, impurities, structural unhomogeneities, and different degrees of chemical segregation. As a result, different surface regions of the workpiece are heated slightly differently. Some



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reach the Curie temperature first and lose their magnetic properties. The relative magnetic permeability of these areas dramatically drop to unity ($\mu = 1$). This leads to a significant increase in the penetration depth in those areas. The resistance of these nonmagnetic regions drastically decrease, creating low resistance paths compared with neighboring surface areas that retain their magnetic properties. As a result, the density of the induced currents in the low-resistance regions will increase. This leads to an increase in power density and an increase in heat sources in these areas. At the same time, there is a redistribution of eddy currents in the workpiece surface. Eddy currents induced in areas that retain their magnetic properties (dark rings) have a tendency to rush to complete their loops through the lower resistance paths (bright rings). This current redistribution leads to a further heat source reduction in the magnetic areas at a low temperature (dark rings) and appears as additional heat sources in the nonmagnetic areas at high temperature (bright rings). Therefore, a chain reaction somewhat similar to positive feedback or "snow ball" occurs. As a result, it is possible to observe with the naked eye a mixture of ring-shaped stripes (Fig. 1) on the workpiece. Hot bright stripes alternate with the relatively cold dark stripes. Experience shows that usually the thickness of the bright and dark stripes equals 1 to 3 current penetration depths in hot steel.

Besides the current redistribution, Type B striping is a result of several other electromagnetic and heat transfer effects, including the electromagnetic edge effect (EEJ) of joined materials having different properties. This effect occurs when conductors with different physical properties are located in a common magnetic field and discussed in Ref.1.

Experience shows that striping can appear in several different ways. However, in the majority of cases, very narrow bright stripes (rings) appear at the beginning of the heating cycle (Fig. 1). Over time, the narrow stripes widen. At this stage, the maximum temperature moves from the center of each ring toward the edges of each bright hot ring. During the heating process, the stripes sometimes move back and forth along the workpiece surface area under the coil. With longer heating cycles, the striping phenomenon usually disappears.

The appearance of the stripes depends on a complex function of the frequency; magnetic field intensity; and thermal, electrical, and magnetic properties and structure of the steel. However, as mentioned above, it can occur only when high power density is applied. If the power density is relatively low, the temperature will equalize between the neighboring bright (high-temperature) and dark (low-temperature) rings because of the thermal conductivity of the steel. Good quality clean steels having a homogeneous structure have less chance to produce this phenomenon. **HTP**

References

1. V. Rudnev, D. Loveless, R. Cook, and M. Black, *Handbook of Induction Heating*, Marcel Dekker Inc., New York, 2003.
2. M. Lozinskii, *Industrial Applications of Induction Heating*, Pergamon Press, London, 1969.