Mysteries in induction heat treating: striping (striation) phenomena

Heat treat practitioners sometimes observe unusual effects in induction heat treating (IHT) of workpieces with seemingly smooth surfaces such as a striping (striation) phenomenon, a barber-pole effect, and snake-skin and fish-tail phenomena, just to name a few [1]. This article will discuss striping (striation) and barber-pole phenomena, their causes, potential impact on parts engineering properties and ways to avoid their appearance.

THREE TYPES OF STRIPING (STRIATION) PHENOMENA

Striping phenomena have been first observed more than 60 years ago, and it may appear on seemingly smooth surfaces of the workpiece. (Note: An appearance of stripes attributed to geometrical irregularities of the workpiece (e.g., such as ball screws and components with threads and teeth) will be excluded from a discussion since the causes of uneven heating in such applications are obvious and related to the electromagnetic proximity effect). Since that time, there were a number of publications devoted to its description, possible causes and prevention [1–7]. Generally speaking, there are three types of striping phenomena:

- Electromagnetic-caused striping (Type A)
- Electromagnetic-caused striping (Type B)
- Quench-related striping (Type C), also referred to as the barber-pole effect.

Two types of striping phenomena are attributed to an electromagnetic origin: Type A and Type B. These phenomena may appear when a single-shot or static heat mode is used. Although the appearance of both types is similar, the physics behind each is quite different.

ELECTROMAGNETIC-CAUSED STRIPING: TYPE A

The Type A striping phenomenon appears only when a multiturn coil is used, and can be observed when heating both ferrous and nonferrous alloys, 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 pattern (also referred to as striations or alternating bright and dark rings) along the length of the workpiece with a seemingly smooth surface, such as the case of straight cylinder shafts.

Stripes are caused by localized power surpluses owing 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 largely as a result of the electromagnetic proximity effect. If the heat time is sufficiently long, the thermal conductivity equalizes the thermal gradients, making stripes disappear. The appearance of this phenomenon can easily be predicted using computer modeling. Proper coil design (including slight increase in turn-to-workpiece gap and/or reduced spacing between turns), selection of process parameters and rotation of the heated workpiece can eliminate this undesirable phenomenon.

ELECTROMAGNETIC-CAUSED STRIPING: TYPE B

The Type B striping phenomenon (Fig. 1) usually occurs only during intensive induction heating of ferrous alloys, including carbon steels where relatively short heat times and high-power densities are used. Multiple stripes can be observed by the naked eye on the surface of a heated workpiece even in the case when a single-turn inductor is used.

Because of Type B striping, the workpiece area under the coil may unexpectedly start to heat non-uniformly. Shortly after the heating cycle begins, alternating hot bright areas (bright stripes) and cold areas (dark stripes) become visible. When dealing with cylinder workpieces, these bright and dark stripes encircle the cylinder, and, thus, have shapes of rings. In contrast to Type A striping, the number of rings with Type B striping is not necessarily related to the number of coil turns. For example, Fig. 1, left reveals that multiple stripes appeared when heating a steel bar utilizing a conventionally wound four-turn cylindrical coil (frequency is 10 kHz). Fig. 1, right shows numerous stripes appearing while heating a wide strip using a single-turn rectangular inductor (frequency is 450 kHz).

Type B striping has been relatively seldom viewed in practical applications or in laboratory experiments and is considered by many as a mysterious phenomenon. In some applications, striping suddenly occurs and then disappears using seemingly identical process recipe and steel grade. There were a number of attempts to explain this phenomenon. Some researchers also tried to recreate conditions for its appearance using computer modeling. However, assumptions and dramatic simplifications made in those studies did not always result in convincing explanations.

There is no single explanation for this phenomenon. M. Lozinskii attempted to explain it in the 1960s [2]. Assume that a magnetic...
steel cylinder is located inside a cylindrical inductor. As a result of the electromagnetic field produced by the induction coil, induced eddy currents will flow within the workpiece. Because of the skin effect, these eddy currents appear primarily in the surface layer of the cylinder located inside the coil, causing an increase of its surface temperature.

In reality, any material has certain microscopic and macroscopic defects, impurities, structural heterogeneities, geometrical deviations and different degrees of chemical segregation. As a result, different surface regions of the workpiece are heated slightly differently. Some reach the Curie temperature first and lose their magnetic properties. The relative magnetic permeability of these areas dramatically drop to unity ($\mu_r = 1$). This leads to a significant increase in eddy current penetration depth $\delta$. The resistances 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.

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 low resistance 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 on the surface of cylinders (Fig. 1, left) or rectangular shaped workpieces (Fig. 1, right). Hot bright stripes alternate with the relatively cold dark stripes. Experience shows that usually the thickness of the bright and dark stripes equals one to three current penetration depths in hot steel.

Besides the current redistribution, Type B striping potentially might also be the result of several other electromagnetic and heat transfer phenomena, including the electromagnetic edge effect of joined materials having different properties. This effect has been studied in [1]. It occurs when conductors with different physical properties are located in a common magnetic field. Experience shows that striping can appear in several different ways. In some cases, very narrow bright stripes (rings) appear at the beginning of the heating cycle. Over time, the narrow stripes may widen and the peak temperatures may move from the center of each ring toward the edges of each bright hot ring. During the heating, the stripes can sometimes move back and forth along the workpiece surface area, climaxing a mystery of this phenomenon. With longer heating cycles, the striping phenomenon usually disappears.

The occurrence of the stripes depends on a complex function of the frequency; magnetic field intensity; and thermal, electrical, and magnetic properties and microstructure of the steel. However, as mentioned above (if it occurs), the needed condition appears to be an application of relatively high-power density. 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. It appears that steels with substantially heterogeneous structures as...
well as so-called dirty steels have a greater chance of exhibiting striping. Good quality clean steels with a homogeneous structure have a lower chance of producing this phenomenon, though there were claims that this phenomenon appeared even when heating ultralow-carbon steels.

There are some other types of striping phenomena during heating. [1] discusses a striping phenomenon with the stripes/ striations occurring in strip-coating applications such as galvanizing and tin reflow that are typically longitudinally oriented. The nature and causes of such striping phenomenon are very different compared to the phenomena discussed above and possibly associated with elastic buckling of the strip due to magnetic pressure. Discussion of this type of striping is outside of the scope of this article.

QUENCH-RELATED STRIPING: TYPE C

The Type C striping phenomenon [1] can be observed upon quenching of uniformly heated workpieces using either a single-turn or multiturn scan inductor with or without part rotation. Frequently, the striping phenomenon that appeared after quenching is often called a quench-striping effect, a quench striation or a barber-pole effect. The cause of its appearance might not relate to the specifics of heating, but is primarily associated with the characteristics of quenching and process recipe including but not limiting to:

- Part rotation
- Specifics of spray quench flow along the workpiece surface after the spray quench impinged (struck) its surface
- Scan speed
- Presence of quench interruptions, its nonuniformity or formation of local steam pockets, and others.

According to my knowledge, the barber-pole effect has never been obtained by mathematical modeling. It has only been observed (Fig. 2). Barber-pole stripes are usually of spiral shapes that could occur on the surface of an as-quenched workpiece and are typically related to surface conditions (e.g., roughness), nonuniform cooling, surface oxidation, and scale formation.

In some cases, the barber-pole effect might not be associated with any appreciable microstructural variations of as-hardened areas and would not affect part performance. Therefore, in cases when the visual appearance of the surface is not critical, the bar-
Fig. 3: Formation of upper transformation products within the as-quenched martensitic structure or the appearance of undesirable tempered martensite can be attributed to the barber-pole effect as well. (Courtesy of Michael O’Brien, BSc [Met], MIEAust, CPEng, Principal Consultant Metallurgist.)

ber-pole effect might only be aesthetically unpleasing but has no detrimental effect on the heat-treated part performance. However, in other instances (Fig. 3), the barber-pole effect can appreciably alter industrial characteristics of materials and the microstructure of the hardened pattern because of improper quenching or interrupted (or partial) quench flow. Formation of upper transformation products (including lower and upper bainite and pearlite) within the martensitic structure or the appearance of undesirable excessively tempered back martensite can be attributed to the barber-pole effect as well, leading to a combination of hard and soft (partially hardened) striations or rings. Experience shows that improvement in quench flow, its severity, and uniformity, or applying a quench follower, as well as making improvements in the eccentricity of a rotated part and modifying the impingement of spray strokes, helps to avoid the appearance of the barber-pole effect.

Induction heat treaters may also refer to the barber-pole effect as a phenomenon that has no association with the appearance of any stripes, rings, or spirals. However, sometimes, during induction heating of cylinders, instead of stripes, a shifted or squeezed temperature profile suddenly appears at the end of the hardened pattern instead of a straight heating pattern. This can take place when using a single-turn or multiturn scan inductor and it does not appear to be related to the helix of a multiturn coil winding. This phenomenon is usually quite unstable, and when the next part is heated, this type of barber-pole effect could disappear and may never be seen again. If this type of barber-pole effect is steady, it can be eliminated by slightly changing the scan speed, coil power, or part rotation speed.

LITERATURE


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