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INDUCTION HEATING Q&A

This month's column features the answers to two questions from readers about what can be done to prevent rust staining from the quenchant, and what causes soft spots and how can they be eliminated.

Question: After running powder metallurgy parts with a heavier production schedule for about 2 to 3 months, we started seeing rust stains mostly local to the single-shot induction hardened area. When we changed the quenchant, the corrosion disappeared. After 1 to 2 months, we again saw corrosion. Changing the quenchant cleared the problem again. We keep our polymer quenchant between 4 and 6% solution, and it is monitored daily. We heard that adding small amounts of bleach helps to stretch out the time between flushes. What is the recommended practice? Does induction heating promote corrosion?

Answer: Biological degradation of the quenchant can result in a reduction of pH value causing solution to become acidic, which can promote excessive corrosion due to acid attack. Among other factors, the rate of corrosion also depends upon a type of quenchant. For plain water and most water-base polymer-type quenchants, the severity of corrosion rate dramatically increases when the pH is less than 6. The intensity of the rate of corrosion increases when pH decreases, somewhat of a "snow-ball" effect. This is why it is preferable to have pH values greater than 7. Too high of a pH level (pH>12, for example) also is not desirable, because it can potentially cause phenomena called caustic cracking and caustic gouging. Typically, pH values between 8 and 9 are considered to be the most desirable unless a membrane separation is used, in which case there is a specific pH range for the solution to be maintained to ensure stability of the membrane[1]. This should be checked with your suppliers and you should review ASTM D6666-01a: Standard Guide for Evaluation of Aqueous Polymer Quenchants.

Induction does not promote any appreciable corrosion. However, it is well-established that corrosion intensity increases with increasing temperature (regardless of whether the temperature increase is after induction heating or any other heating means, assuming that the rest of conditions remain the same).

Therefore, if selected regions of the heat treated part have different temperatures, then areas at higher temperatures will experience greater corrosion compared with areas at lower temperatures. The reason why rust stains were mostly local to the induction hardened area is related to the presence of a residual heat at those locations.

Under no circumstances should bleach or swimming-pool chemicals be added to quenchants as an attempt to stretch out the time between flushes. This will cause further degradation of the polymer, and possibly lead to the formation of chloroethers, which are considered by many as carcinogenic[1]. A study conducted by K.P. Kirkbride and H.J. Kobus[2] shows that at a certain concentration, there is even danger of an exothermic reaction leading to an explosion and skin burns.

Question: For quite a while, we experience low hardness readings (52-55 HRC) after a scan hardening operation in areas where the diameter of our 1045 steel hollow shaft changes. We have consulted with induction heating specialists but still have not eliminated the problem. What causes soft spots at these locations and how we can fix this problem?

Answer: Based on the hardening properties of AISI 1045 steel, it is reasonable to expect achieving an as-quenched surface hardness of about 60-62 HRC [3,4]. Under normal conditions, a surface hardness in the range of 52-55 HRC is lower than expected as-quenched hardness. Generally, there are three groups of factors that could potentially cause the appearance of soft spots:

- Metallurgical/microstructural factors (flaws in the steel's prior structure, chemical and phase segregation, decarburization, etc.)
- Inappropriate heating conditions (insufficient austenitization or formation of heterogeneous austenite)
- Quench related factors

The second and/or third factors are most likely responsible for an appearance of soft spots because the location of low hardness regions is related to diameter change areas.

Case hardening of solid shafts vs. hollow shafts

Induction surface (case) hardening of hollow shafts has unique features compared with hardening of solid shafts. With solid shafts, the core temperature typi-

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cally does not rise significantly during heating. The relatively cold core compliments spray quenching by increasing the cooling intensity of shaft surface (cold-sink effect)[4,5]. By comparison, with hollow shafts, the cold-sink effect is dramatically reduced or even can be reversed by reducing cooling severity during quenching. Numerical computer modeling helps reveal subtleties of induction case hardening by evaluating the shaft's thermal conditions that are difficult to see or to measure.

Uncovering scan-hardening subtleties via computer modeling

Induction heating is a complex combination of electromagnetic, heat transfer, and metallurgical phenomena[4]. Heat transfer and electromagnetics are non-

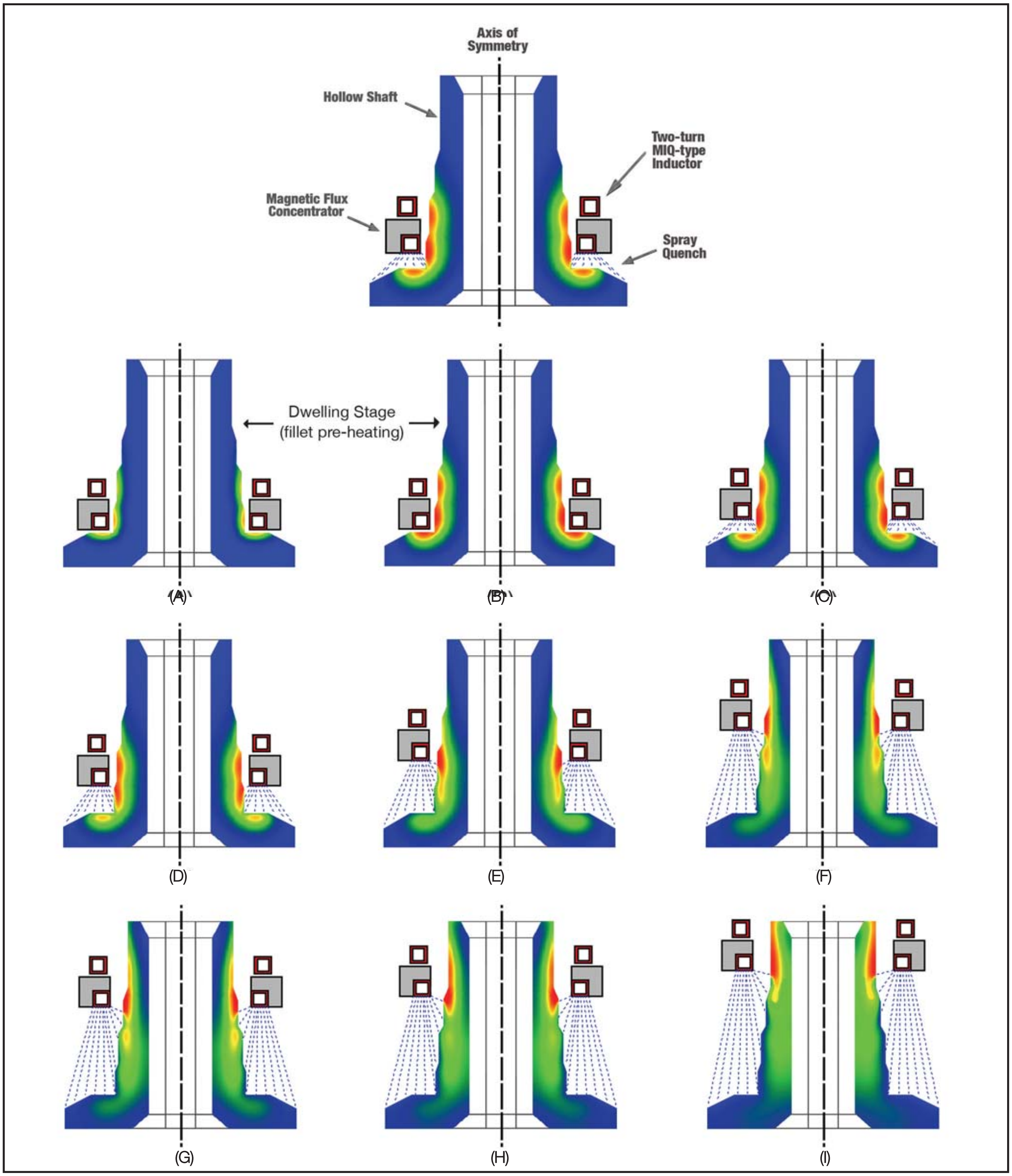

Fig. 1 — Computer model of the sequential dynamics of induction scan hardening a hollow shaft using a two-turn MIQ (machined integral quench) inductor with an "L"-shaped flux concentrator ring (frequency = 9 kHz).

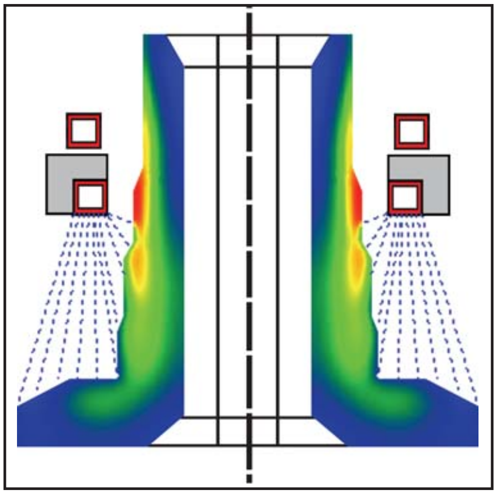

Fig. 2 — Magnified temperature pattern of an intermediate process stage of scan hardening a shaft showing the comet-tail effect.

linear and tightly coupled due to the interrelated nature of physical properties of steel. The metallurgical phenomenon is also a nonlinear function of temperature, heating intensity, cooling severity, chemical composition, prior microstructure, and other factors.

Figure 1 shows the results of computer modeling the sequential dynamics of induction scan hardening a hollow shaft using a two-turn MIQ (machined integral quench) inductor with an "L"-shaped flux concentrator ring (frequency = 9 kHz). At the beginning (Fig.1 A and B), a 2.6 second power dwell is applied to properly harden the shaft fillet area. During this stage, an inductor is energized but does not move and quenching is not applied. Upon completing the dwell stage, the shaft fillet is sufficiently preheated and scanning begins. Scan rate and coil power are varied during scanning to allow proper accommodation of changes in shaft geometry.

Computer modeling reveals several important process subtleties:

• During scanning, appreciable heating of the shaft begins at a distance a good deal above the top copper turn creating a preheating effect. Factors responsible for preheating are heat flow in the axial direction due to thermal conduction, propagation of the external magnetic field, and generation of heat sources outside of induction coil.

• Presence of an external magnetic field outside the induction coil is also responsible for the post-heating of shaft areas located immediately below the bottom turn, and, in some cases, even in regions where the quenchant impinges the shaft surface. With insufficient quenching, the latter can dramatically reduce quenching severity and potentially create conditions for crossing the nose of the CCT (continuous cooling transformation) curve, resulting in the formation of mixed structures with the presence of upper transformation products (e.g., bainitic/pearlitic structures or "ghost" networking). Such microstructures are notorious for scattering and lower hardness readings.

• Electromagnetic proximity effect and coil end effect[4] both cause the hot spots appearing on a shoulder near a shaft diameter change. During scanning, the magnetic field preferably couples to the shoulders leading to a power density surplus at those locations. The presence of hot spots produced by power surplus necessitates having prolonged cooling to remove excessive heat, ensuring martensitic formation and obtaining sufficient hardness at these locations. At the same time, a heat source deficit could occur in the undercut region and transition area near the shaft's smaller diameter.

"Comet- tail" effect

It is imperative to take into consideration a comet-tail effect when developing a scan hardening process recipe. Figure 2 shows a magnified temperature pattern of an intermediate process stage (Fig.1 F). The comet-tail effect manifests itself as a heat accumulation in shaft subsurface regions below the scan inductor, being pronounced in the areas of a diameter change. Upon quenching, the temperature of shaft surface can be cooled sufficiently below the M_s temperature. At the same time, the heat accumulated in the shaft subsurface might be sufficient for tempering back of as-quenched surface regions, leading to soft spots.

Critical issue with computer modeling

A limitation of many commercial induction heating software programs is that they are not capable of taking into consideration a comet-tail effect when trying to model induction scan hardening. In addition, some software cannot properly handle pre- and post-heating effects that

appear due to external magnetic field propagation and axial thermal conduction. These restrictions dramatically limit their use. When designing inductors and developing optimal process recipes, it is imperative to properly model both heating and spray-quenching stages. Otherwise, crucial aspects of the process might be missed, having a negative impact on modeling accuracy and usefulness.

Trouble-shooting soft spots

There are several factors responsible for the appearance and prevention of soft spots, assuming an absence of flaws in a steel's prior structure:

1) If scattered soft spots are localized to fillets, undercuts, and areas of transition from larger-to-smaller diameters, and if metallographic examination reveals low hardness readings associated with the appearance of "ghost" pearlite, or an excessive amount of free ferrite, then, most likely, the problem is related to incomplete austenitization. The microstructure formed upon quenching heterogeneous austenite typically consists of a combination of lower and upper transformation products, causing the appearance of soft spots. *Solution*: Appropriate increases in coil power, a slight reduction of scan speed near the low hardness region, and using lower frequency can improve the kinetics of austenite formation there.

2) Where the appearance of lower-than-expected hardness occurs only in a shoulder area, soft spots can be caused by the following factors:

- Reduced hardness could be a result of undesirable tempering back due to the comet-tail effect if metallographic examination reveals the presence of tempered martensite within as-quenched structure. Greater case depths result in a corresponding increase of subsurface heat accumulation.
- If metallographic examination reveals the presence of upper transformation products, quench severity is less than required for martensite formation and the cooling curve entered the upper transformation region of the steel's CCT diagram.

Solution: It is important to continue quenching the shaft after coil power is off regardless of whether the shaft surface appears to be sufficiently cooled down. This ensures removal of the heat retained in the shaft subsurface and sufficient compensation for a comet-tail effect. In both cases, improvement in quench severity (i.e., flow rate increase) and/or extending quench time by using a quench follower[4,5] will fix the problem.

3) Due to the complexity of the electromagnetic field in a diameter change area, there is always a reasonable compromise between a surplus of induced power in the shoulder of the large diameter and its deficit in the fillet or undercut of the neighboring smaller diameter area. *Solution*: Process controllability can be improved by applying a coil having a narrower face, or by lowering frequency.

4) Shaft orientation during scan hardening also can influence the appearance of scatter hardness within the diameter change region. Figure1 shows the preferable shaft orientation for scan hardening. For a shaft oriented in the opposite direction, certain areas of the shaft transition zone may not be quenched sufficiently, and spray quench strokes could miss the diameter change areas resulting in insufficient quenching and the appearance of soft spots.

Question: We witness reverse hardness in our induction through hardening application; the core hardness is greater than the surface hardness. What can cause it?

Answer: There are at least five factors that can cause reverse hardness. One of next installments will discuss this phenomenon and its prevention. **HTP**

References

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