

Quench and Tempering Tubular Products

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With the cost of steel going up precipitously, methods of providing higher-strength, lower-weight designs have become keenly important. This scenario is very true in tubular goods. The use of heat-treated, high-strength steel alloys allows the tube and pipe products to have thinner walls, thus lighter weight, without sacrificing strength.

For the sake of this article, the selection of the steel grade will not be discussed. The writer assumes that metallurgical and mechanical engineers were consulted for the selection of the steel to be used in a given application. Heat-treatable materials, however, are a requisite part of the application. Heat treating steel for optimum strength and ductility consists of a hardening process followed by tempering. Hardening steel increases its tensile strength and abrasion resistance but also reduces its ductility. Hardened steel is relatively brittle due to the residual stresses and the typical characteristics of the hardened microstructure – martensite. By sacrificing some strength and wear resistance, ductility can be introduced again by tempering the material.

Tempering is accomplished by reheating the already hardened material to a temperature significantly below that used for the hardening process. In the tempering process, residual stresses are relieved, and the hardened microstructure is altered to allow greater toughness and ductility

while marginally reducing hardness (wear resistance) and overall strength. This mill processing sequence is often referred to as “quench and temper.”

Heating Process

Induction heating provides an excellent methodology for “quench and temper” processing. Heating is quick and uniform. Due to the relatively short heating times, scale formation and decarburization of the surface are generally minimal. Parts are usually heat treated one at a time, providing consistent results part after part. Warm-up time is minimal – generally less than one hour for the quench system – and there is no need to keep expensive furnaces running during off-production hours in order to maintain process temperature and avoid lengthy warm-up times. Modern material-handling systems allow multiple heating and quenching processes to be integrated into one cell with proper sequential timing while occupying minimal floor space.

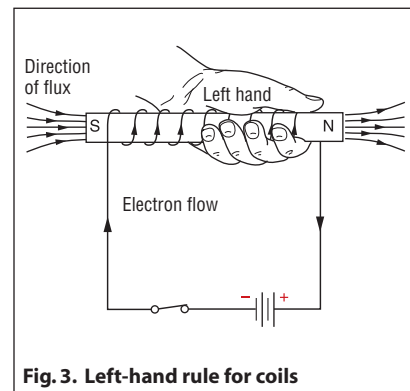
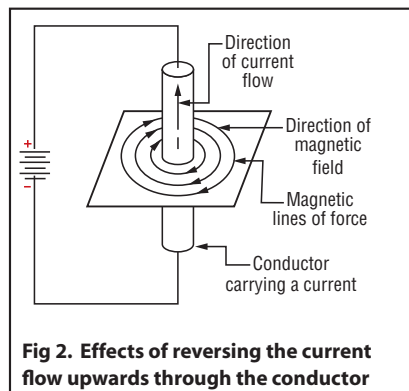
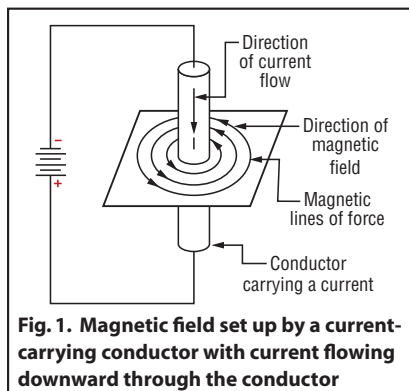
Unlike most other heating processes

where thermal energy is transferred from the surface through the cross section of a part, induction heating heats from within the part. Induction heating is an electrical process for heating a metal object whereby eddy currents are generated within the metal and that metal’s resistance to the eddy current flow leads to Joule heating of the metal. Eddy currents are induced by way of electromagnetic radiation.

The Induction Process

Whenever electrical current flows in an electrically conductive material, a magnetic field is produced around that conductor. The polarity of the magnetic field is determined by the polarity of the electrical current flow (Figs. 1 and 2).

Figure 1 shows the polarity of the magnetic field with a current flow downward through the conductor. It should be noted that the magnetic field is flowing in a counter-clockwise direction. Figure 2 shows the effects of reversing the current flow upwards through the conductor. It should be noted that the magnetic field flows in



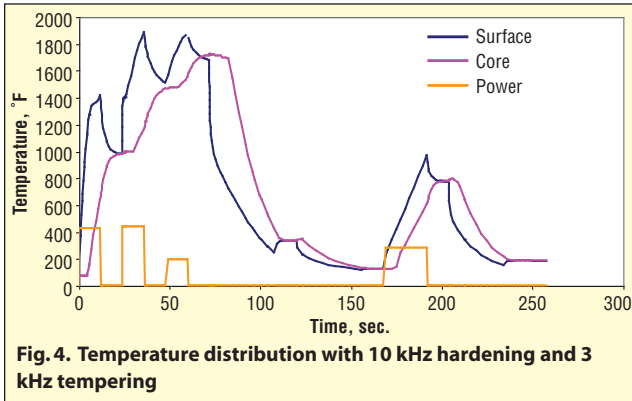


Fig. 4. Temperature distribution with 10 kHz hardening and 3 kHz tempering

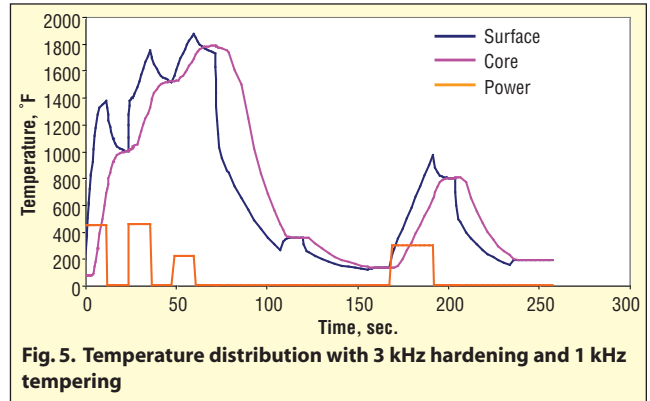


Fig. 5. Temperature distribution with 3 kHz hardening and 1 kHz tempering

a clockwise direction, indicating a change in magnetic polarity.

Additionally, when the electrical conductor is formed in such a way as to allow magnetic lines of force to mutually couple, a stronger magnetic field is formed. A typical shape for the coil is a helix, as shown in Figure 3. This figure demonstrates the “left-hand” rule for coils. Imagine grasping the coil with the left hand, fingers pointing in the direction of current flow. The thumb will point to the coil’s north pole. As current changes direction, so does the relative position of the north pole.

By replacing the battery with an alternating current source – like an induction-heating current power supply – the electromagnetic field will change polarity with each half-cycle and constantly change in intensity as the sinusoidal waveform moves through its cycle. Placing a second electrically conductive material in relative close proximity to this constantly changing magnetic field will induce an electrical current flow in that material. This is the premise behind induction heating. The induction-heating system (coil and power source) is specifically designed to induce sufficient electrical current as to heat

the target material to the required temperature in the required length of time.

The induced currents are equally affected by skin-effect as direct applied currents. Skin-effect is the tendency of high-frequency currents to flow towards the surface of the part. As such, the depth of penetration can be controlled by selecting the appropriate frequency – the number of times the magnetic field alternates polarity. Higher frequency produces high degrees of skin-effect. By selecting the appropriate frequency, heating at the desired depth is controlled and predictable.

The depth of penetration of electrical currents is determined by the formula

$$d = 3160 \sqrt{\rho/Mf}$$

where: d = depth of penetration in inches, ρ = electrical resistivity in ohm-in, μ = magnetic permeability, f = applied frequency in Hertz.

The depth of penetration is defined as the distance below the surface whereby the induced power density is reduced to 14% of its value at the surface. From this formula, it can be understood that lower frequency and higher electrical resistivity control the depth of penetration.

Coil / System Design

Using this knowledge in a modern coil design, one can confidently determine the optimum frequency for a given application. Figure 4 represents a coil/thermal design using 10 kHz for hardening and 3 kHz for tempering.

This calculation was made assuming a 5.75-inch-diameter pipe having a 5/8-inch wall thickness. The pipes were approximately 40 feet long and were scanned at a rate of 1.0 inch/second. Each of the hardening coils was 12 inches long, and the tempering coil was 24 inches long. The dark-blue line represents the external surface temperature. The pink line represents the internal surface temperature. The orange line represents induction-coil power. This particular calculation required three induction-heating coils (for hardening) with a 12-inch gap between coils. The gaps between the coils were intended to prevent overheating the surface and allow the internal surface to continue heating after surface heat was suspended. The system was designed to heat the entire cross section to approximately 1750°F (954°C) as it entered the quench station. It should be obvious that the sharp reduction in temperature was due to quenching.



Fig. 6. Entrance end of a 40-foot horizontal scanner processing a 5 3/4-inch-diameter pipe with a 5/8-inch wall

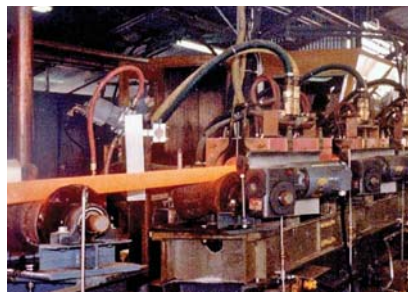


Fig. 7. A system employing skewed rolls as the drive mechanism



Fig. 8. Pusher-lance for precise heat treating of tubular products



Fig. 9. Quench barrel for small-diameter, heavy-wall tubular products

Each quench station was 36 inches long. Two were required for hardening, while only one was required for post tempering.

Figure 5 represents the same processing cycle except the hardening frequency was 3 kHz and the tempering was accomplished at 1 kHz. The graph clearly demonstrates improved temperature uniformity through the cross section. For this reason, this was the hardening/tempering power combination chosen for the application.

Overall straightness of the final product was critical to the customer. The material-handling system was designed with a lance-pusher rather than a typical skewed-roll drive (Figs. 7 & 8). A skewed-roll drive places undesired force upon the pipe while it is at the elevated temperature. Since steel is relatively soft at typical hardening temperatures, the force exerted by the skewed roll imparts distortion into the pipe. In this new design, a series of long rolls were aligned using a laser device. The key to minimizing distortion was to maximize the support of the pipe while at the elevated hardening temperatures. No more than 18 inches of pipe was unsupported in this application. The lance sealed the end of the pipe while it pushed it through the system. The rolls provided rotation and support. Distortion was reduced to less than 0.030 inch over 3 feet of length, well within the customer's specification of 0.045 inch maximum.

Quenching

Quenching is as critical to the hardening process as heating. In order to transform the heated material into martensite, the cooling process must be fast. Slower cool-

ing rates allow other undesirable microstructures such as bainite and pearlite to form. Unfortunately, there is a possibility of cooling some steel grades too quickly, resulting in quench cracks. Cracking can be eliminated by controlling the quench-fluid temperature and/or adding a material to the quench that is intended to retard and control the quenching rate. Close control and monitoring of the quench concentration levels are vital to a successful process. Excessively high concentration levels will render low hardness, while excessively low concentration levels will promote cracking.

Uniform application of the quench fluid around the perimeter is equally important to ensure proper hardness and minimal distortion. Quench rings should be designed with internal baffles to ensure uniform pressure around the perimeter. The baffle also eliminates the potential of high portal pressures adjacent to the inlet connections. Several quench rings are generally required to prevent excessive distances between support rolls.

Tempering

As stated earlier, tempering is accomplished by reheating hardened material to a temperature well below that required for hardening. This reapplied heat relieves the residual stresses in the part created by the hardening process and toughens the hardened microstructure (martensite) to increase ductility. The reheating is typically done in an oven at 275-450°F. Parts are held at temperature for an hour prior to slow cooling. Comparable results can be accomplished by heating very quick-

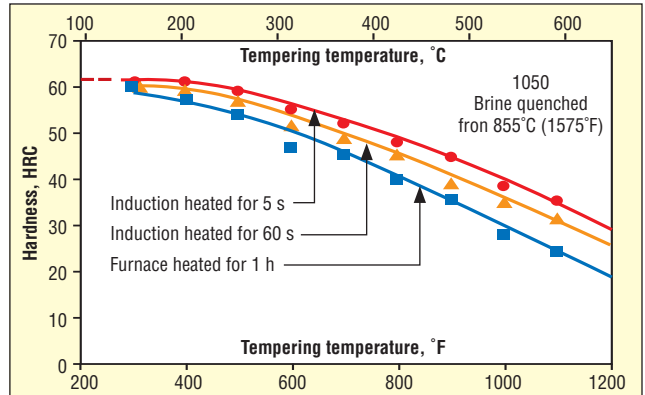


Fig. 10. Surface hardness as a function of tempering temperature for furnace and induction heating of SAE1050 steel quenched in brine from 1575°F

ly with the induction-heating process. However, the temperature must be several hundred degrees above that normally considered appropriate for tempering in an oven. The material used in the subject application would normally be tempered in an oven at 450°F. Using an induction-heating process, the surface was heated to 975°F within 24 seconds. This provided enough tempering to relieve the residual stresses and provide the desired ductility.

To determine if the quench and tempered part was successfully processed, the material must undergo complete mechanical tests for tensile, yield and elongation. Although hardness can be an indication that the material was properly processed, it should not be the determining criteria. Other factors (such as improper microstructure) can yield a similar hardness reading that could result in lower-strength material. Hardness should instead be used as a spot check on a verified process to determine the process consistency. Periodic mechanical tests should be performed to assure the process integrity. **IH**

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Additional related information may be found by searching for these (and other) key words/terms via BNP Media SEARCH at www.industrialheating.com: quench and temper, magnetic field, eddy current, frequency, residual stress, ductility