INDUCTION HEATING AND HEAT TREATING FOR AEROSPACE APPLICATIONS

Induction heating is used to produce high quality, reliable aerospace components as well as unique combinations of engineering characteristics.

Valery Rudnev, FASM*
Inductoheat Inc., Madison Heights, Mich.

Electromagnetic induction is used for heating ferromagnetic and nonmagnetic metallic alloys, as well as certain composite materials. Induction heating (IH) generates heat internally at well-defined regions on the workpiece, which shortens process cycle times and results in high production rates. Heat intensity can range from high (exceeding 800°C/s for gear hardening) to moderate (as low as 2°C/s for tempering and stress-relieving). Highly controllable heat intensity enables optimizing a wide variety of processes (Fig. 1).

Due to the electromagnetic skin effect in induction heating, approximately 86% of induced power (heat generation) is concentrated within the surface layer of the workpiece. This is often called current penetration depth (δ), which is proportional to the square root of electrical resistivity (ρ) and inversely proportional to the square root of frequency and relative magnetic permeability (μ_r) of the material being heated. Lower frequencies promote deeper heat generation, while higher frequencies produce more shallow heat generation.

Heat generation from induction heating of electrically conductive materials occurs by two mechanisms[1]. The primary mechanism is associated with the Joule effect, which is often referred to as I^2R heating; the magnitude of heat generation is proportional to the product of the material's electrical resistance and the square of the total current induced within it. The second mechanism occurs in heating ferromagnetic materials (e.g., carbon steel), and is associated with magnetic hysteresis (magnetization-demagnetization cycles). Thermal energy is dissipated during the reversal of magnetic domains due to internal friction. Magnetic hysteresis heat generation is proportional to the applied frequency and the area of the hysteresis loop, which is a complex function of chemical composition, grain size, temperature, magnetic field intensity, and frequency.

Intrinsic characteristics of induction heating that make it attractive for use in aerospace applications include:

- Repeatable quality with piece-by-piece processing capabilities and individual component traceability. Highly accurate process monitoring systems are available including profile/signature monitoring.
- Selective heat generation capability, which is advantageous in applications including band annealing and bending, end heating, brazing, and selective hardening.
- More energy efficient and environmentally friendly than other heating methods including gas-fired furnaces, salt and lead baths, and carburizing and nitriding systems.
- Advantages in safety (no combustion or environmental contaminants), reduced labor cost for machine operators, and automation capability.
- Shorter startup and shutdown times, eliminating or significantly reducing idle periods of unproductive heating. No energy is needed to build or maintain heat in non-operating conditions.

Fig. 1 — The highly controllable heat intensity of induction heating enables optimizing a wide variety of heating and hardening processes.

Member of ASM International

- Easier to incorporate protective and reducing atmospheres into IH system design compared with the majority of alternative heating methods.

While not all aerospace components are well suited to IH, applications that benefit from the process include:

- Band annealing of fasteners and sleeves made of alloy steels, precipitation-hardenable (PH) stainless steels, Ni-Cu-Fe alloys, Ti and Al alloys, and others
- Curing/polymerization of composites containing dispersed ferromagnetic nanoparticles (energy dissipation via internal heat generation for developing required chemical reactions)
- Heating prior to warm and hot working, heading, and thread rolling of steels and special alloys
- Processing of motor rotors, tubes, wires, cables, and rods
- Joining applications including bonding, brazing, and soldering

SURFACE HARDENING OF GEARS, SHAFTS, AND PINS

In contrast to carburizing and nitriding, induction hardening does not require heating the entire gear, pinion, or pin. Heating can be localized in areas where metallurgical changes are desired (Fig. 2). Often, it is desirable to obtain a contour-like hardening pattern to optimize gear performance characteristics and reduce distortion. Such a pattern maximizes the beneficial compressive stresses within the case depth, thus inhibiting crack development. Compressive residual stresses of 400 to 550 MPa are commonly achieved at the tooth surface by applying single-frequency heating. The magnitude of residual stresses depends on the material, its prior microstructure, hardness pattern, and process recipe. Shorter heating times usually produce higher compressive residual surface stresses.

Simultaneous dual-frequency technology helps to optimize hardness patterns. The core of this technology is associated with development of solid-state power supplies capable of producing two substantially different frequencies simultaneously that can be applied to a hardening inductor. Lower frequency helps austenitize the roots of the teeth while high frequency helps austenitize the flanks and tips, minimizing heating time. A new technology from Inductoheat (Statipower IFP) enables instant, independent adjustment of frequency (from 5 to 60 kHz) and power (up to 450 kW) in a preprogrammed manner during the heating cycle, optimizing electromagnetic, thermal, and metallurgical conditions.

Shot peening applied after induction gear hardening further increases compressive residual stresses at the surface and subsurface, improving fatigue and bending strength and preventing pitting.

Fig. 2 — Induction heating enables heat generation in localized areas where metallurgical changes are desired.

Rapid heating affects austenite formation kinetics considerably, shifting it toward higher temperatures according to continuous heating transformation (CHT) diagrams. Orlich et al.[2] conducted a comprehensive study of CHT diagrams for steels to determine the correlation of heat intensity versus the positions of A_{c1}, A_{c2}, A_{c3}, and A_{cm} critical temperatures, and the ability to obtain homogeneous austenite. Experiments were conducted for a variety of steels taking into consideration a wide range of heating rates (from 0.05° to 2400°C/s).

The data show that for induction hardening, when heat intensities exceed approximately 20°C/s (typical for the majority of induction hardening applications), rapid heating can switch the order to A_{c2}, A_{c1}, and A_{c3} instead of the normal order of A_{c1}, A_{c2}, and A_{c3}. This phenomenon is a commonly overlooked metallurgical subtlety of induction heating, and is essential to take into consideration for some induction heating applications, potentially shifting a relatively easy job to an almost impossible one.

SUPERHARDNESS PHENOMENON

When induction hardening steels, the so-called *superhardness* or super hardening phenomenon can occur[1,3]. This phenomenon refers to obtaining greater hardness levels in the induction surface-hardened case compared with hardness levels typically expected based on Jominy hardenability curves. The surface hardness of an induction surface hardened part could be 2-4 HRC higher (1-3 HRC being more typical) than that expected for a given carbon content for parts with identical chemical compositions.

The superhardness phenomenon is not clearly understood, and its basis has not been established nor widely accepted by metallurgists worldwide. However, it has been obtained experimentally on numerous occasions and several interpretations have been offered[1,3].

INDUCTION HARDENING STAINLESS AND SPECIALTY BEARING STEELS

Martensitic stainless steels (MSS), precipitation-hardenable (PH) stainless steels, and specialty bearing steels specified in certain aerospace applications can be induction hardened, forming a martensitic structure in the as-quenched condition. Electromagnetic and thermal properties of these alloys are noticeably different compared with those of plain carbon steels, which influences process recipe selection.

Electrical resistivity (ρ) and magnetic permeability (μ_r) of MSS are greater and lower, respectively, compared with those of plain carbon steels with similar carbon content. For example, at room temperature, ρ of MSS is typically two to three times higher than those of corresponding plain carbon steels. Both parameters produce a greater depth of heat generation (δ) for a given frequency. In addition, depending on the grade of MSS, the Curie temperature can be 40-60°C lower compared with plain carbon steels, which shortens the magnetic stage of the heating cycle.

While martensitic stainless steels have the highest thermal conductivity among other stainless steels, their values can be 30% to 45% lower than plain carbon steels. Therefore, there is a noticeably lower heat transfer effect, potentially resulting in greater surface-to-core thermal gradients during rapid induction heating, as well as the occurrence of a higher magnitude of transient stresses and greater probability of crack development, suggesting the need to apply lower heat intensities.

The initial microstructure of MSS before induction hardening is often annealed or martempered. Somewhat longer austenitizing times and higher temperatures are commonly specified due to slow dissolution of chromium carbides during austenitization. Some complex carbides may still remain upon completion of the austenitization stage. The as-quenched hardness of many MSS can be represented by a bell-shaped curve due to several factors; initially, hardness increases with a rise in austenitizing temperatures, reaching a maximum and then starting to decline[1]. Excessively high austenitizing temperatures should be avoided, because they produce coarse grains and a greater amount of retained austenite (RA) upon quenching to room temperature. This may necessitate short soaking/holding at austenite phase temperatures.

The as-quenched microstructure of MSS, PH stainless steels, and specialty bearing steels can contain a substantial amount of RA. Thus, a subzero cryogenic treatment followed by single or double tempering is commonly specified. The presence of greater than expected amounts of RA might also be associated with a stabilization phenomenon, which can be caused by an interrupted quench. Stabilization often occurs in hardening alloys with sufficiently low M_s and M_f temperatures. Lower amounts of RA are formed during uninterrupted quenching. An interrupted quench with a considerable quench delay at both room and low-range elevated temperatures can stabilize the austenite, exhibiting a greater amount of RA. This phenomenon introduces certain restrictions for a time delay between quenching and cryogenic treatment. ~**HTPro**

Note: Statitron is a registered trademark and IFP is a trademark of Inductoheat Inc. Some of the information presented here was first published in the Handbook of Induction Heating, 2nd Edition, by V. Rudnev, D. Loveless, and R. Cook, CRC Press, 2017. CRC Press has granted permission to publish these materials.

For more information: Valery Rudnev is director, science and technology, Inductoheat Inc., an Inductotherm Group Co., 248.629.5055, 248.310.2741 (mobile), rudnev@inductoheat.com, www.inductoheat.com.

References

1. V. Rudnev, D. Loveless, and R. Cook, *Handbook of Induction Heating,* 2nd ed., CRC Press, 2017.
2. J. Orlich, A. Rose, and P. Wiest, *Atlas zur Warmebehandling der Stahle,* Vol 4, Zeit-Temperatur-Austenitisierung-Schaubilder, Verlag Stahleisen M.B.H., Düsseldorf, Germany, 1976.
3. D. Matlock, Metallurgy of Induction Hardening of Steel, *Induction Heating and Heat Treating,* Vol 4C, *ASM Handbook,* (V. Rudnev and G. Totten, Eds.), ASM International, p 45-57, 2014.