by Valery I. Rudnev, FASM, Inductoheat Group

Professor Induction welcomes comments, questions, and suggestions for future columns. Since 1993, Dr. Rudnev has been on the staff of Inductoheat Group, where he currently serves as group director – science and technology. In the past, he was an associate professor at several universities. His expertise is in materials science, metallurgy, heat treating, applied electromagnetics, computer modeling, and process development. Dr. Rudnev is a member of the editorial boards of several journals, including *Microstructure and Materials Properties* and *Materials and Product Technology.* He has 28 years of experience in induction heating. Credits include 16 patents and 128 scientific and engineering publications.

Contact Dr. Rudnev at Inductoheat Group
32251 North Avis Drive
Madison Heights, MI 48071
tel: 248/629-5055; fax: 248/589-1062
e-mail: rudnev@inductoheat.com
Web: www.inductoheat.com

Metallurgical insights for induction heat treaters

PART 2: SPRAY QUENCHING SUBTLETIES

This is the second part of the series that alternates with "Systematic analysis of induction coil failures." There have been 11 installments in the coil failures series. Part 12 will be published in the September/October HTP.

Spray quenching is typically used in induction hardening applications.[1,2] In induction hardening of cylindrically shaped parts (axle shafts, spindles, rods, camshafts, and gears, for example), spray quenching works best if the component is rotated during the quenching operation, which ensures cooling uniformity (Fig. 1). By rotating parts, the workpiece essentially experiences a constant impingement rather than many small impingements. Uneven quenching typically has a negative effect on microstructure and could make distortion and cracking problems more pronounced.

Quench holes in the tooling are typically placed facing the heated component at 3/16 to 1/4 in. (~5 to 6 mm) intervals in a staggered pattern. The orifice size is related to the specifics of quenching requirements, including coil-to-workpiece geometry, the air gap between the quench block and the workpiece surface, quench concentration, and required flow. In some cases, the quench system is built into the coil,[1] while a barrel or quench block is separate from the induction coil in other cases.

The intensity of spray quenching (intensity of heat removal) depends on the quenchant flow rate, the angle at which the quenchant strikes the workpiece, and the temperature, purity, and type of quenchant, as well as the part's temperature. Quenchants used include water, aqueous polymer solutions, and, to lesser extent, oil, water mist, and forced air. Water and aqueous polymer solutions are the most popular.

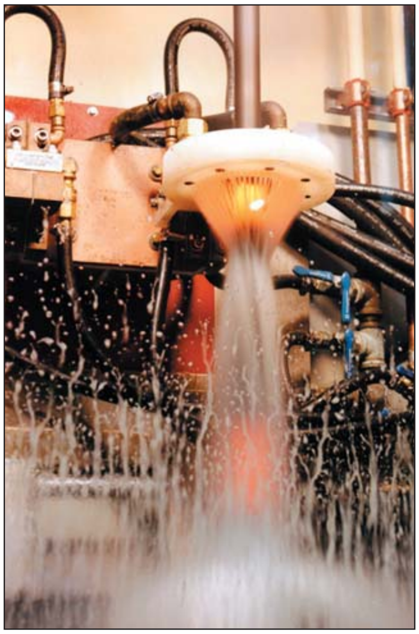

Fig. 1 — When induction hardening cylindrically shaped parts, spray quenching ensures uniform cooling.

Differences in cooling curves

There is a common misunderstanding regarding the ability to apply the widely published, classical cooling curves for immersion quenching to induction hardening applications. Classical cooling curves (Fig. 2) representing three stages of quenching — vapor blanket (Stage A), nucleate boiling (Stage B), and convective cooling (Stage C) — cannot be applied directly to spray quenching. The differences are both quantitative and qualitative, and include, but are not limited to, specifics of film formation and heat transfer through the vapor blanket during the initial stage (A), as well as the kinetics of formation, growth, and removal of bubbles from the surface of the heated component during nucleate boiling (Stage B).[3]

Due to the nature of spray quenching, Stages A and B are greatly suppressed in time, while cooling during the convection stage (C) is noticeably more intense, compared with the process represented by classical cooling curves.

Also, the thickness of the vapor blanket film during Stage A is typically much thinner during spray quenching than when the part is submerged in a quench tank, and depends on flow rate, impingement angle, part rotation, and other characteristics of the quenching system. This vapor film is unstable and could be frequently ruptured.

In addition, the transition between Stages A and B is smoother with spray quenching than that shown by classical cooling curves for immersion quenching. During nucleate boiling (Stage B), bubbles are smaller because they have less time to grow. And much larger numbers of bubbles form during spray quenching and the intensity with which they remove heat from the surface of the component is substantially greater compared with immersion quenching.

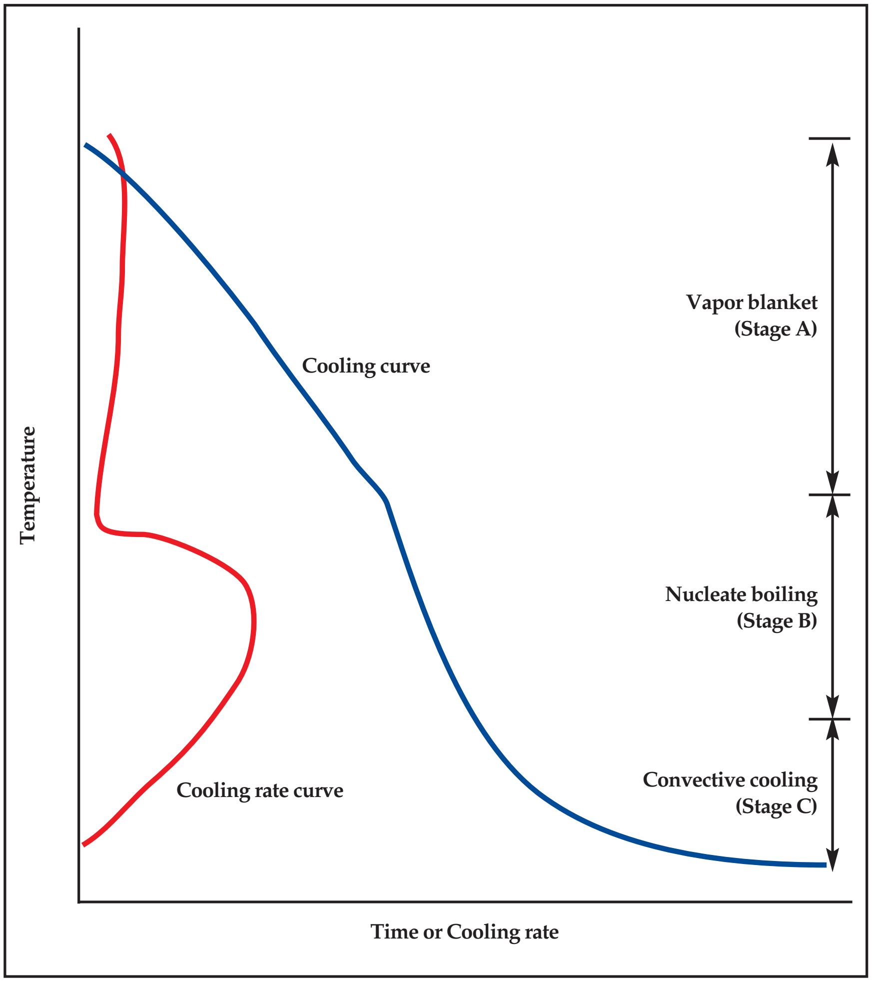

Fig. 2 — Classical cooling curves for immersion quenching (Ref. 4). These curves have only limited application to induction surface hardening.

Cold sink effect

Another factor that has a considerable effect on quench severity in surface hardening by induction is the "thermal sink" effect provided by the component's "cold" core. In the majority of induction surface hardening applications, the core temperature does not rise significantly, due primarily to a pronounced skin effect,[1] high heat intensity, and short heating time. As a result, heat transfer from the surface of the workpiece to its core during the heating stage is not sufficient to significantly raise core temperature. A cold core complements spray quenching by further increasing the cooling intensity at the surface and in subsurface regions of the part.

Note that in some induction surface hardening applications that require shallower case depths (0.02 to 0.1 in. [0.5 to 2.5 mm]), self-quenching can be used. Here, the effect of thermal conduction away from the surface by a sufficiently cold core provides a cooling intensity that's high enough to miss the nose of the continuous cooling curve. This technique (also called "mass" quenching) allows a shallow case to be obtained without the use of a liquid quenchant.[1]

Spray quenching benefits

Consequently, classical cooling curves for immersion quenching are of only limited value in induction hardening applications. The more intensive quench severity provided by spray quenching in induction hardening provides higher hardnesses and higher compressive surface stresses, compared with conventional immersion quenching.

More information about spray quenching and designing quench systems for induction hardening can be found in References 1 and 3–6.

References

1. *Handbook of Induction Heating*, by V. Rudnev, D. Loveless, R. Cook, and M. Black: Marcel Dekker Inc., New York, 2003, 800 p.

2. "Be aware of the 'Fine Print' in the science of metallurgy of induction hardening: Part 1," by V. Rudnev: *Industrial Heating*, March 2005, p.37–42.

3. *High-Frequency Induction Heat Treating*, by G. Golovin and M. Zamjatin: Mashinostroenie, St. Petersburg, Russia, 1990.

4. *Handbook of quenchants and quenching technology*, by G. E. Totten, C. E. Bates, and N. A. Clinton: ASM International, Materials Park, Ohio, 1993, 507 p.

5. "Designing quench systems for induction hardening: Part 1," by D. Poteet, G. E. Totten, and L. C. F. Canale: *Industrial Heating*, November 2005, p. 43–46.

6. "Designing quench systems for induction hardening: Part 2," by D. Poteet, G. E. Totten, and L. C. F. Canale: *Industrial Heating*, December 2005, p. 35–40.