Residual stresses in induction hardening: simply complex

PROFESSOR INDUCTION

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Professor Induction welcomes comments, questions, and suggestions for future columns. Since 1993, Dr. Valery 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, where he taught graduate and postgraduate courses. His expertise is in materials science, heat treating, applied electromagnetics, computer modeling, and process development. He has 28 years of experience in induction heating. Credits include 15 patents and 118 scientific and engineering publications. He also is coauthor of the 800-page Handbook of Induction Heating *(published in 2003 by Marcel Dekker, www.dekker.com). Contact Dr. Rudnev at Inductoheat Group, 32251 North Avis Drive, Madison Heights, MI 48071; tel: 248/585-9393; fax: 248/589-1062; e-mail: rudnev@inductoheat.com; Web: www.inductoheat.com.*

Heat treaters are often faced with the necessity of making a reasonable compromise between maintaining the required hardness and obtaining a tough, ductile microstructure that has the desired distribution of residual stresses.[1] (Stresses are closely related to cracking of induction hardened parts, as can be seen in the "fish bone" diagram of cracking discussed in References 1 and 2.)

Stresses can be classified in several different ways, and although residual stresses are three-dimensional — with axial, circumferential, and radial components — this discussion will be simplified by considering them as one-dimensional stresses.

Depending upon the distance over which they extend, residual stresses can be "macroscopic" or "microscopic." Macroscopic stresses typically appear at a distance that exceeds several grains of metal.[3] In contrast, microstresses take place within a grain, and include stresses that appear on the atomic level. Studies of residual stresses in metal heat treating typically focus on the distribution and magnitude of macrostresses.

Stress groups: In general, stresses that appear during induction heat treating can be divided into three groups: initial, transitional, and residual stresses.[1]

- *Initial stresses:* Their distribution and value depend upon the operations that preceded heat treatment (casting, forging, rolling, and/or welding, for example).
- *Transitional stresses:* These stresses appear during heating and cooling, and, depending upon the application, may partially or totally disappear after heat treatment has been completed.
- *Residual stresses:* They are the product of initial and transitional stresses.

How residual stresses arise

Let's examine how residual stresses form during induction hardening.[1] Note that the mechanism is different from that associated with other heat treating processes, including gas carburizing and nitriding.

In general, two types of stress are encountered: thermal and phase transformation stresses. Thermal stresses are caused by different magnitudes of temperature and temperature gradi-

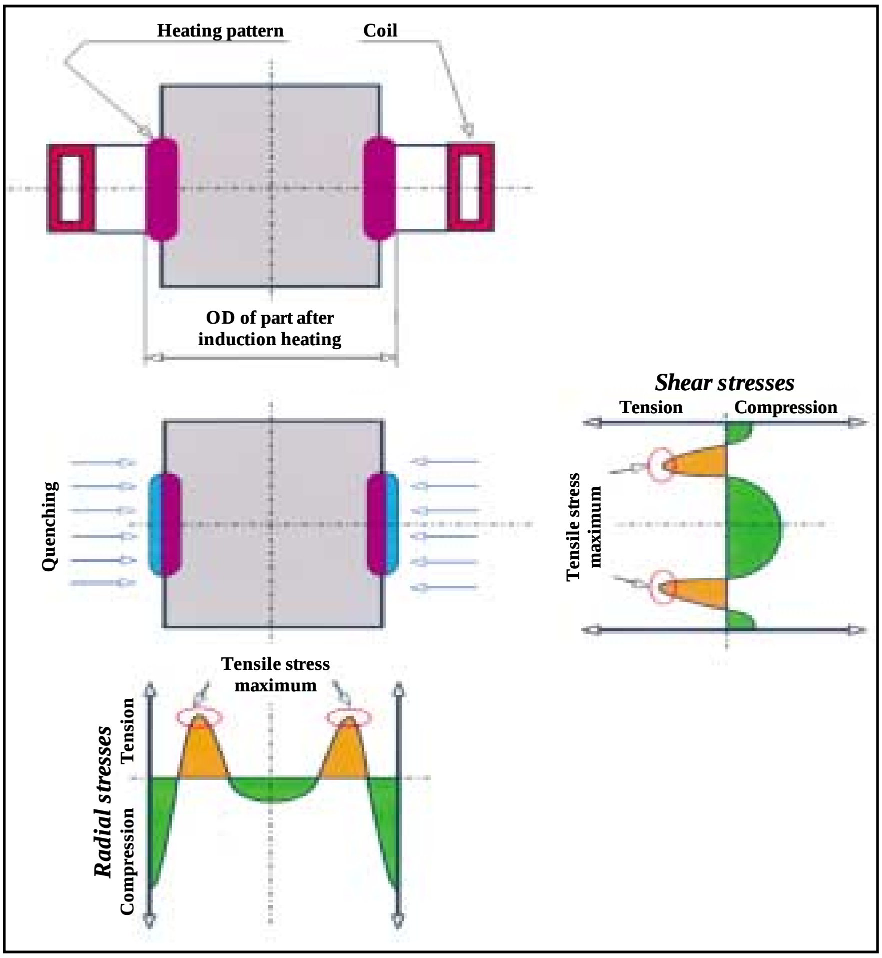

Fig. 1 — Formation of residual stresses after induction hardening.

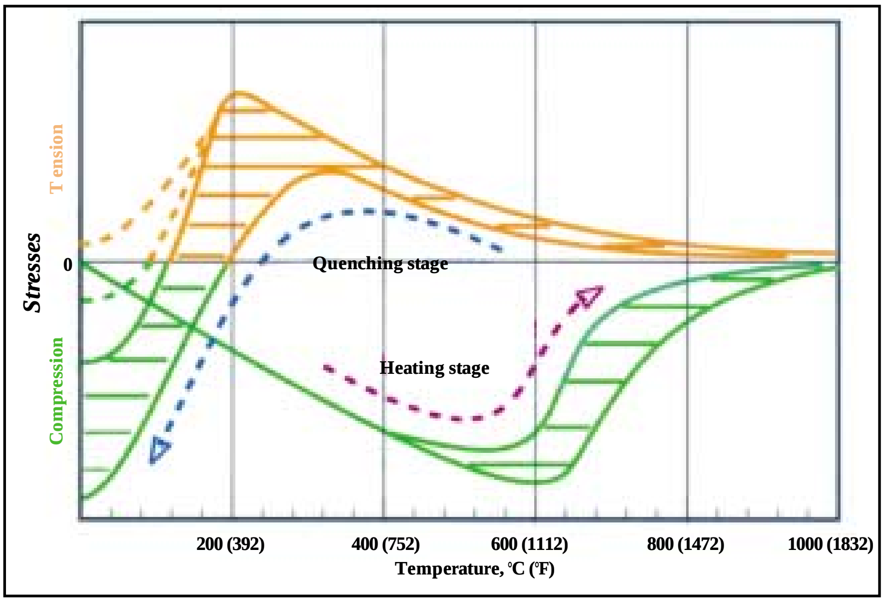

Fig. 2 — Stresses at the surface of a carbon steel cylinder during "heating-quenching" cycle.

ents, while transformation stresses primarily occur due to volumetric changes accompanying the formation of phases such as austenite, bainite, and martensite. The total stress is a combination of the two components. At different stages of heat treating, the effect of the components on total stress also will differ.

Example: Figures 1 and 2 illustrate the dynamics of (macroscopic) stress appearance during induction hardening of a carbon steel cylinder.[1,4,5] At the first stage of the heating cycle, the section of the cylinder located under the coil will "try" to expand. The temperature of the workpiece at this point is relatively low: less than 500°C (930°F). Carbon steel in this temperature range is in a "nonplastic" condition and cannot easily expand. The result: compressive stresses build up in the surface of the workpiece.

Heating: As the temperature rises, surface compressive stresses form and increase in magnitude (Fig. 2). In the 520 to 750°C (970 to 1380°F) range, steels undergo plastic volumetric expansion and stresses begin to decrease. Finally, when the temperature exceeds approximately 850°C (1560°F), the steel's surface freely expands, and the diameter of the heated area becomes greater than its initial diameter. Since the yield point of the surface layer is considerably lower at elevated temperature, the material will flow plastically and surface stresses will significantly decrease.

Cooling: After quenchant is sprayed onto the heated surface, the outermost layer quickly loses its plasticity and a pronounced tensile stress maximum appears at the surface of the workpiece (Fig. 2). This maximum value typically occurs just above M_s (martensite start) temperature. The appearance of martensite reduces surface tensile stresses and leads to the formation of surface compressive stresses. Upon completion of cooling, a complex combination of compressive and tensile stresses exists within the part (Fig. 1).

It is important to remember that the residual stress system is self-equilibrating; that is, there is always a balance of stresses in the workpiece. If certain regions have compressive residual stresses, then somewhere else there must be offsetting tensile stresses. If the stresses weren't balanced, "movement" would then result.

Benefits: Surface compressive residual stresses are considered useful in most applications. They provide some protection against crack initiation and propagation caused by stress risers; for example, microscopic scratches, notches, and microstructural heterogeneities. Compressive residual stresses are particularly beneficial to parts that experience bending and / or torsion in service.

Tensile residual stresses, on the other hand, can be dangerous. Note the tensile stress maximum located just beneath the hardened case in Fig. 1. These are the stresses primarily responsible for subsurface crack initiation.

Relieving, measuring stress

The overall residual stress condition of the induction hardened part usually increases its brittleness and notch sensitivity, which reduces toughness and reliability. Therefore, stress relief is required. Goals are to reduce subsurface tensile stresses and move the tensile stress maximum farther from regions of applied stress, while retaining the useful surface compressive stresses. Stress relieving during induction tempering is discussed in Ref. 1. In addition, a final grinding operation also can have a pronounced effect on residual stress distribution and crack sensitivity.[6] Grinding should be considered when developing the required residual stress distribution.

Measurements: Residual stress distributions are not nearly as simple in induction hardened parts of complex shape as they are in a plain cylinder. As a result, measurement of residual stresses is often not an easy task, and special equipment and a great deal of time may be needed. Techniques for quantifying residual stresses include the sectioning, hole drilling, layer removal, bending deflection, X-ray diffraction, magnetic, and ultrasonic methods.[3] Important process selection factors include the specifics of the heat treated part; for example, kind of metal, grain size, and required inspection depth and accuracy. **HTP**

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. "Troubleshooting Cracking in Induction Hardening," by V. Rudnev: *Heat Treating Progress*, Vol. 3, No. 5, August 2003, p. 27–28.
3. *Handbook of Measurement of Residual Stresses*, Society for Experimental Mechanics, Jian Lu (Ed.): Fairmont Press Inc., Lilburn, Ga., 1996, 238 p.
4. *High-Frequency Induction Heat Treating*, by G. Golovin and M. Zamjatin: Mashinostroenie, Saint Petersburg, Russia, 1990, 230 p. (in Russian).
5. *Industrial Applications of Induction Heating*, by M. Lozinskii: Pergamon Press, London, 1969, 420 p.
6. "A Review of the Influence of Grinding Conditions on Resulting Residual Stresses After Induction Surface Hardening and Grinding," by Janez Grum: *Journal of Materials Processing Technology*, Vol. 114, Issue 3, 7 Aug. 2001, p. 212–226.