Spin hardening of gears revisited

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. 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.

In recent years, gear manufacturers have gained additional knowledge about how technology can be used to produce quality parts. The application of this knowledge has resulted in gears that are quieter, lighter, and lower cost, and have an increased load-carrying capacity to handle higher speeds and torques while generating a minimum amount of heat.

Role of induction hardening

Not all gears are well suited for induction hardening. For example, bevel, hypoid, and noncircular gears are rarely heat treated by induction. On the other hand, external spur and helical gears, worm gears, and internal gears, racks, and sprockets are among those that typically are induction hardened (Fig. 1).

Gear performance characteristics (including load condition and operating environment) dictate the required surface hardness, core hardness, hardness profile, residual stress distribution, grade of steel, and the prior microstructure of the steel. (Gear hardening patterns and their effects on load-carrying capacity and service life are evaluated in Ref. 1.)

In contrast to carburizing and nitriding, induction hardening does not require heating the whole gear. With induction, heating can be localized to only those areas in which metallurgical changes are required. For example, the flanks, roots, and tips of gear teeth can be selectively hardened.

A major goal of induction gear hardening is to provide a fine-grain martensitic layer on specific areas of the part. The remainder of the part is unaffected by the induction process. Hardness, wear resistance, and contact fatigue strength increase. Depending on the application, tooth hardness after tempering typically is in the 48 to 60 HRC range.

Another goal of induction gear hardening is to produce significant compressive residual stresses at the surface and in a subsurface region.[1] Compressive stresses help inhibit crack development and resist tensile bending fatigue.

Selecting gear steels

Gear operating conditions, the required hardness, and cost are important factors to consider when selecting materials for induction hardened gears. Carbon and low-alloy steels containing 0.40 to 0.55% carbon are commonly specified. Examples: AISI 1045, 1552, 4140, 4150, 4340, and 5150.

Repeatability of the hardness pattern is strongly affected by the consistency of the steel's microstructure prior to induction hardening and chemical composition.

A "favorable" initial microstructure — homogeneous, fine-grain, quenched and tempered martensitic structure, 30 to 34 HRC — promotes a rapid, consistent induction hardening response with minimum shape/size distortion and minimum grain growth. This type of initial microstructure requires a lower-than-usual austenitizing temperature for formation of homogeneous austenite. What results after quenching is a crisp hardness pattern with a narrow transition zone (compared with that of a gear having a ferritic/pearlitic initial microstructure).

Structures to avoid: "Unfavorable" structures are those that contain a significant amount of coarse pearlite and, most importantly, coarse ferrites or clusters of ferrites. Gears having this structure require longer austenitizing times and/or higher austenitizing temperatures to complete diffusion-type processes and ensure that homogeneous austenite is obtained.[1]

Ferrite is practically a pure iron and does not contain the carbon required for martensitic transformation. That's why large areas (clusters) of free ferrite require a longer time for carbon to diffuse into low-carbon regions. Ac-

Fig. 1 — External spur and helical gears, worm gears, and internal gears, racks, and sprockets are among those that typically are induction hardened (examples shown here). Bevel, hypoid, and noncircular gears are rarely heat treated by induction. (Courtesy Inductoheat Inc.)

tually, clusters of ferrites act as one very large grain, which often will be retained in the austenite. What can result after quenching is a ferritic/pearlitic network and/or a complex ferritic/martensitic structure with scattered soft and hard spots.[1] Consequently, gears having segregated and banded initial microstructures should be avoided.

Steels having large carbides (spheroidized microstructures) also offer a poor response to induction hardening, and require longer heating times and higher temperatures for austenitization. Prolonged heating leads to grain growth, the appearance of coarse martensite, data scatter, a wider transition zone, and gear shape distortion.

Other factors: Induction heat treatment can be appreciably affected by variations in the chemical composition of the steel. Therefore, a “favorable” initial metal condition also requires close control of composition within the steel’s specification limits.

Special attention also should be paid to the design of induction hardening machines for powder metallurgy (P/M) gears. Unlike cast and forged gears, the properties of P/M gears can be greatly affected by variations in the starting material — electrical resistivity, thermal conductivity, and magnetic permeability strongly depend on density. Variations in the porosity (density) of the P/M steel can result in hardness value scatter and variations in case depth and residual stress data.[1,2]

The surface condition of the gear is another factor that can have a pronounced effect on gear hardening. Stress concentrators such as voids, microcracks, notches, and other surface and subsurface discontinuities can initiate cracking during the “expansion-contraction” cycle of induction hardening. Thermal gradients and stresses can reach critical values, causing notches and microcracks to “open.”

Design tip: Gear teeth should be generously chamfered. Overheating of sharp edges and corners due to the electromagnetic edge effect can occur at high frequencies, which may result in weakened teeth.[1]

Coil designs, heating modes

Depending upon the required hardness pattern and tooth geometry, gears are induction hardened by encircling the part with a coil (so-called “spin hardening”) or, for larger gears, heating them “tooth-by-tooth” or “gap-by-gap.”[1] Spin hardening is particularly appropriate for gears having fine- and medium-size teeth. Gears are rotated during heating to ensure an even distribution of energy.

Spin hardening: When applying encircling coils, there are five parameters that play important roles in obtaining the required hardness pattern: frequency, power, cycle time, coil geometry, and quenching conditions. Different patterns can be produced by properly controlling these parameters. Figure 2 shows a variety of induction hardened patterns for the same carbon steel shaft. They were produced in the lab by varying heating time, frequency, and power.

As a rule, when it is necessary to harden only the tooth tips, a higher frequency and high power density should be applied (Fig. 3, left). To harden only the tooth roots, use a lower frequency (Fig. 3, right). A high power density generally gives a shallow pattern, while a low power density will produce a deep pattern with wide transition zones. Hardness pattern uniformity and repeatability depend strongly on the relative positions of gear and induction coil, and the ability to maintain the gear concentric to the coil.

There are four popular heating modes used for the induction spin hardening of gears that employ encircling-type coils: the conventional single-frequency, pulsing single-frequency, simultaneous dual-frequency, and pulsing dual-frequency concepts.[1] All four can be applied in either a single-shot or scanning heat treating approach. The choice of heating mode depends upon the application and equipment cost.

Fig. 2 — A variety of hardened patterns can be obtained by varying induction heating time, frequency, and power. (Courtesy J. LaMonte, Inductoheat Inc.)

Fig. 4 — Induction spin hardening of a large gear. The heated gear will be quenched by immersion. (Courtesy Inductoheat Inc.)

Gear quenching

Remember that hardening is a two-step process: heating and quenching. Both are important. There are three

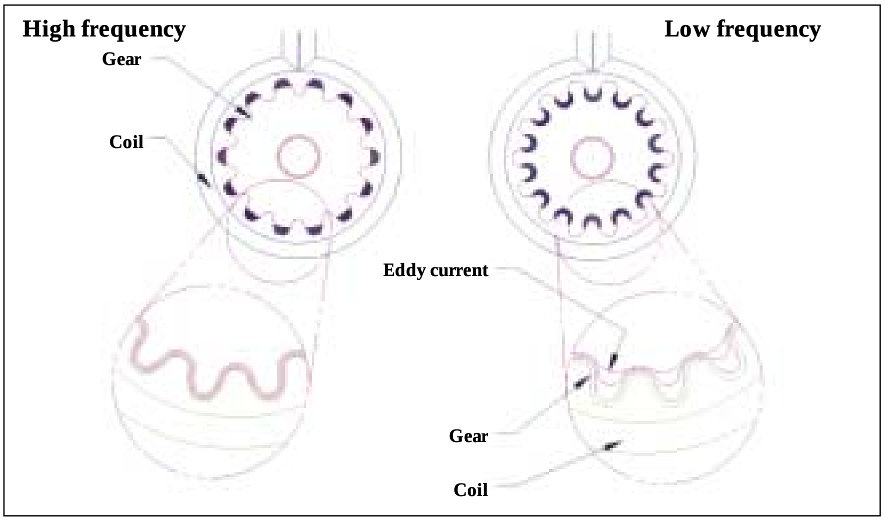

Fig. 3 — Effect of high frequency, left, and low frequency, right, on the eddy current flow when using an encircling induction coil. Use a high frequency to harden only the tips of gear teeth.

ways to quench gears in spin hardening applications.

- Submerge the gear in a quench tank. This technique is particularly applicable for large gears (Fig. 4).
- Small- and medium-size gears are usually quenched "in-place," using an integrated spray quench.
- Use of a separate, concentric spray-quench block (quench ring) located below the inductor.

Note that the widely published, classical cooling curves that represent the three stages of quenching — vapor blanket, boiling, and convection heat transfer — cannot be applied directly in spray quenching. Due to the nature of spray quenching, the first two stages are greatly suppressed. At the same time, cooling during the convection stage is more severe.

Tooth geometry and rotation speed are other major factors that have a pronounced effect on quench flow and cooling severity during gear quenching.

It also is important to avoid both eccentricity of the inductor and quench system relative to the gear and gear wobbling. Even with gear rotation, gear wobbling will cause a specific part of the gear to be hotter, because it will be closer to the coil. Besides nonuniform heating, wobbling also causes uneven quenching, leading to additional gear shape distortion.

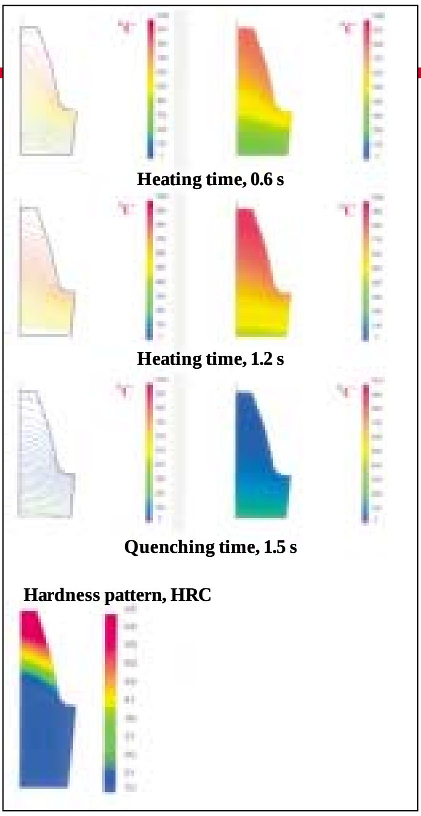

Fig. 5 — Dynamics of induction hardening fine-pitch gears using a frequency of 300 kHz. Computer modeling data.

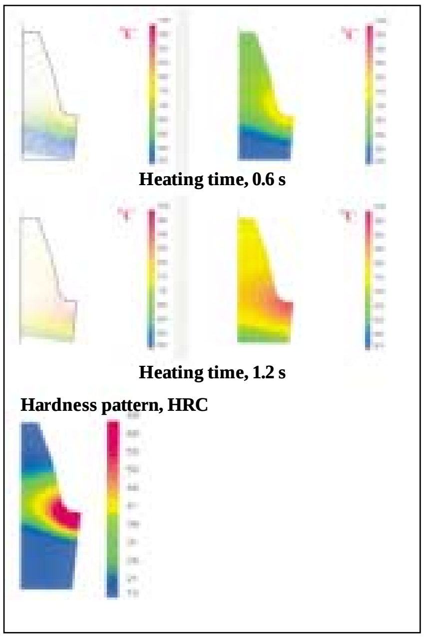

Fig. 6 — Dynamics of induction hardening fine-pitch gears using a frequency of 10 kHz. Computer modeling data.

Computer modeling

Computer modeling is a major factor in the successful design of induction heating systems, providing the ability to predict how different factors and process parameters may influence transitional and final heat treating conditions. Modeling delineates what must be accomplished in the design of the system and/or process recipe to improve the effectiveness of the heat treatment and guarantee that the required results are obtained.

By its very nature, induction heating is characterized by a close relationship to the physical properties of the metal being heated.[1] Some properties strongly depend upon the temperature of the metal and its microstructure, while others are functions of magnetic field intensity and frequency as well. During the heating cycle, significant changes occur in such important properties as thermal conductivity, specific heat, magnetic permeability, and electrical resistivity. Variations in magnetic permeability and electrical resistivity result in an increase in the current penetration depth of up to 16 times during the heating cycle. Such a dramatic change leads to a considerable three-dimensional redistribution of the heat induced in the part during the heating cycle.[1] This explains why variation in physical properties should be taken into consideration when computer modeling an induction gear hardening process.

For example, Figures 5 and 6 show the dynamics of temperature distribution during heating and quenching of a fine-pitch gear using radio frequency (RF) and low frequency, respectively.

High frequency: As expected, when an RF frequency of 300 kHz is applied, an eddy current induced in the gear follows the contour of the gear (see Fig. 3, left). Since the highest concentration of current density will be in the tip of the tooth, there will be a power surplus in the tip compared with the root. Also taking into account that the tip of the tooth has the minimum amount of metal to be heated, compared with the root, the tip will experience the most intensive temperature rise during the heating cycle. In addition, from the thermal perspective, the amount of metal beneath the gear tooth root represents a much larger heat sink compared with that beneath the tooth tip.

Another factor that contributes to more intensive heating of the tooth tip is better electromagnetic coupling — the so-called proximity effect — between the inductor and tooth tip, vs. its root. Higher frequency has a tendency to make a proximity effect more pronounced.[1]

These factors combine to provide rapid austenitization of the tooth tip, which, upon quenching, produces a martensitic layer on the tip (Fig. 5).

Low frequency: When a low frequency, such as 10 kHz, is applied for heating fine-tooth gears, the eddy current flow and temperature distribution in the gear tooth will be quite different (see Fig. 3, compare left and right).

A frequency reduction from 300 kHz to 10 kHz noticeably increases the eddy current penetration depth in the steel — from 1 mm to 5.4 mm — particularly at temperatures above the Curie temperature. In a fine-tooth gear, such an increase in penetration depth results in a current cancellation phenomenon in the tooth tip and pitch line area. This makes it much

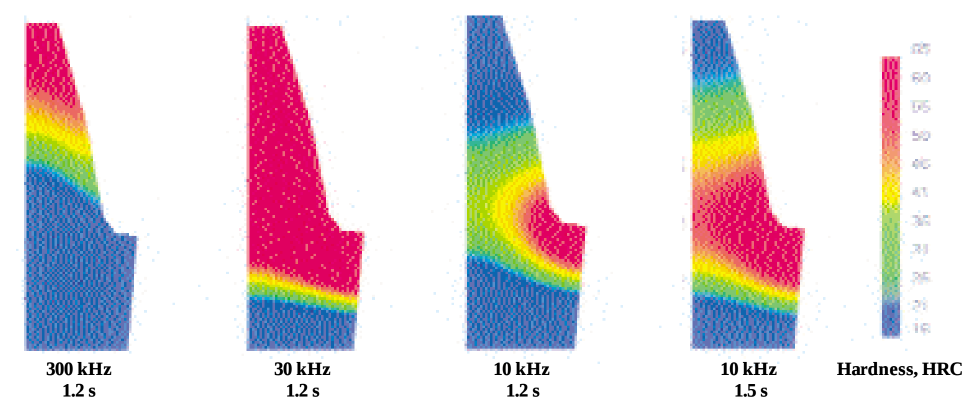

Fig. 7 — How a gear hardening pattern varies with applied frequency. Computer modeling data.

"easier" for induced current to take a "short" path, following the base circle or root line of the gear instead of the tooth profile. The result is more intensive heating of the root fillet area compared with the tip of the tooth (Fig. 6), and the development there of martensite upon quenching.

Hardening patterns: An example of how the gear hardening pattern varies with applied frequency is shown in Fig. 7. These data were obtained by computer modeling using Inductoheat's proprietary ADVANCE-Gear software. The results of modeling support the experimentally obtained hardening patterns shown in Fig. 2, and confirm the previous explanation of the physics of the electrothermal processes that occur during induction spin hardening of gears using different frequencies.

It is important to remember that the terms "high frequency" and "low frequency" are not absolute. For example, depending upon gear geometry, a frequency of 10 kHz might be considered low when heating fine-tooth gears, but would be considered high when hardening large gears having coarse teeth (Fig. 4). Similarly, a frequency of 300 kHz could act as a very low frequency for certain gear geometries, and be able to harden only the root of the tooth and unable to properly harden its tip. **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. [Note: This reference includes additional information about gear spin hardening, as well as "tooth-by-tooth" hardening, "gap-by-gap" hardening, and gear tempering.]

2. "Intricacies of Induction Hardening Powder Metallurgy Parts," by V. Rudnev: *Heat Treating Progress*, Vol. 3, No. 7, November / December 2003, p. 23–24.