Recent Inventions and Innovations in Induction Hardening of Gears and Gear–Like Components

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This paper examines the expanding capabilities of induction hardening of gears through methods like spin hardening or tooth-by-tooth techniques.

Introduction

This presentation provides a review of basic principles and applications devoted to induction hardening of small-, medium- and large-size gears using tooth-by-tooth techniques and encircling method.

Depending upon the gear size, required hardness pattern and tooth geometry, gears are induction hardened by encircling the whole gear with a coil (so-called "spin hardening of gears"), or for larger gears, heating them "tooth-by-tooth" (Refs. 1–6).

Tooth-by-Tooth Hardening

The tooth-by-tooth method comprises two alternative techniques: "tip-by-tip" or "gap-by-gap" hardening (Refs. 1–4).

The tip-by-tip method can apply a single-shot heating mode or scanning mode, while gap-by-gap techniques exclusively apply the scanning mode. Inductor scanning rates are typically within 6 mm/sec to 9 mm/sec. Both tip-by-tip and gap-by-gap techniques are typically not very suitable for small- and fine-pitch gears (modules smaller than 6) (Refs. 1–2).

When using tip-by-tip hardening, an inductor encircles a body of a single tooth. This technique is not often used, because the hardening patterns typically do not provide the required fatigue and impact strength. Gap-by-gap hardening is a much more popular technique compared to the tip-by-tip method. This is the reason why the term tooth-by-tooth hardening is often associated with the gap-by-gap hardening method. Gap-by-gap hardening requires the inductor to be symmetrically located between two flanks of adjacent teeth. Inductor geometry depends upon the shape of the teeth and the required hardness pattern. Special locators (probes) or electronic tracing systems are often used to ensure proper inductor positioning in the tooth space.

Two scanning techniques used include one where the inductor is stationary and the gear is moveable, and the other where the gear is stationary and the inductor is moveable. The latter technique is more popular when hardening large-size gears. Inductors can be designed to heat only the root and/or flank of the tooth, leaving the tip and tooth core soft, tough and ductile (Fig. 1). Though this is one of the oldest hardening techniques,

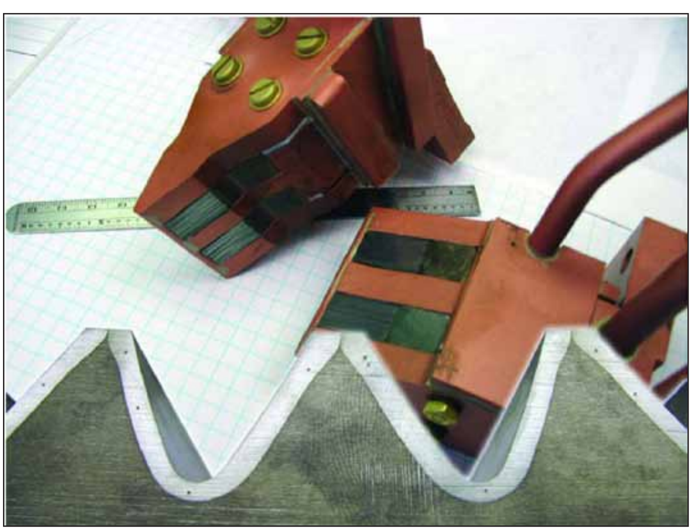

Figure 1 For tooth-by-tooth hardening, inductors can be designed to selectively harden specific areas of gear teeth where metallurgical changes are required (Ref. 2).

Figure 2 Induction gear hardening machine for large bearing ring with teeth located on exterior (courtesy Inductoheat).

recent innovations continue improving the quality of gears heat treated using this method.

Thermal expansion of metal during the heating should be taken into consideration when determining and maintaining the proper inductor-to-tooth air gap. After gear loading and initial inductor positioning, the process runs automatically based on an application recipe. Figure 2 shows examples of a tooth-by-tooth induction hardening machine.

When developing tooth-by-tooth gear hardening processes, particular attention should be paid to electromagnetic end/edge effects and the ability to provide the required pattern in the gear end areas. Upon scanning a gear tooth, the temperature is distributed within gear roots and flanks quite uniformly. At the same time, since the eddy current makes a return path through the flank and, particularly through the tooth tip, proper care should be taken to prevent overheating the tooth tip regions, in particular at the beginning and at the end of the scan hardening. Improved system design helps to maintain required hardness uniformity.

Specifics of gear geometry demand a particular process control algorithm. In the past, the process control recipe was limited to an available variation of power and scan rate vs. inductor position. Recent innovations now enable inverters to independently control both power and frequency during scanning operation, which optimizes electromagnetic and thermal conditions at initial, intermittent and final stages of scanning. As an example, Figure 3 shows Inductoheat's Statipower IFPt (Independent Frequency and Power control) inverter. The ability to independently change during scanning the frequency and power of an induction system represents the long-held dream of commercial induction heat treaters, since such types of set-up would provide the greatest process flexibility. Statipower IFPt is an IGBT-type power supply specifically designed for hardening and tempering applications, allowing independently adjustable frequency via CNC program in a 5-40 kHz frequency range and power in the range of 10-360 kW. This concept substantially expands heat treat equipment capabilities for processing parts by programming power and/or frequency changes on the fly, maximizing heating efficiency and temperature uniformity while heating complex geometry components.

Figure 3 Inductoheat's Statipower IFP is an IGBT-type power supply specifically designed for induction hardening and tempering applications; it provides independently adjustable frequency via CNC programming in a 5–40 kHz frequency range and power in the range of 10–360 kW.

Encircling Hardening Techniques

Gear spin-hardening (encircling inductors). Spin-hardening is the most popular approach for induction hardening gears with fine- and medium-size teeth. Gears are rotated during heating to ensure an even distribution of energy. Single-turn or multi-turn inductors that encircle the whole gear can be used (Refs. 1; 3–6). When applying encircling coils, it is possible to obtain substantially different hardness patterns by varying process parameters.

As a rule, when it is necessary to harden only the tooth tips, a higher frequency and high power density should be applied; to harden the tooth roots, use a lower frequency. A high power density in combination with the relatively short heat time generally results in a shallow pattern, while a low power density and extended heat time produces a deep pattern with wide transition zones.

Figure 4 Contour-hardened gears (courtesy Inductoheat).

Quite often, to prevent problems such as pitting, spalling, tooth fatigue and endurance and impact limitations, it is required to harden the contour of the gear, or to have gear-contour hardening (Fig. 4). This often also maximizes beneficial compressive stresses within the case depth and dramatically minimizes distortion of as-hardened gears keeping it under 80-100 microns (0.003"– 0.004").

Many times, obtaining a true contour-hardened pattern can be a difficult task due to the difference in current density (heat source) distribution and heat transfer conditions within a gear tooth.

Simultaneous dual-frequency gear hardening. Some induction practitioners have heard about simultaneous dual-frequency gear hardening, which utilizes two appreciably different frequencies working on the same coil at the same time (Ref. 6). Low-frequency helps to austenitize the roots of the teeth and high frequency helps austenitize the tooth flanks and tips.

However, it is not advantageous to have two different frequencies working simultaneously all the time. Many times, depending upon the gear geometry, it is preferable to apply lower frequency at the beginning of heating cycle; after achieving a desirable root heating, the higher frequency can complement the initially applied lower frequency, thus completing a job in tandem.

Figure 5 shows a single-coil dual-frequency system that comprises medium-frequency (10 kHz) and high-frequency (120 to 400 kHz) modules working simultaneously— or in any sequence desirable to optimize properties of the heat treated gears (Ref. 6); total power exceeds 1,200 kW. As expected, smaller gears will require less power.

Inductoheat's simultaneous dual-frequency induction gear-hardening system (Fig. 5) also has some "auto-match" items to simplify tuning. It is rugged and can be used for high-volume, single-shot hardening of several powertrain components, dramatically minimizing distortion of heat treated parts and providing a superior hardness pattern with favorable distribution of residual stresses.

Novel development in induction gear-hardening—TSH steels. There was a belief that not all gears and pinions were well-suited for induction hardening. Hypoid and bevel gears, spiral bevel automotive pinions and noncircular gears used to be rarely induction-hardened and typically carburized. This situation has been changed. As an example, Figures 6a and 6b show an example of inductively case-hardened components (Refs. 7–8).

Figure 5 **Inductoheat's simultaneous dual-frequency inverter for gear contour hardening (courtesy Inductoheat).**

TSH steels are low-hardenability (LH) low-alloy steels characterized by limited hardenability and a reduced tendency for grain growth during heating into the hardening temperature range. They can be substituted for more expensive standard steels typically used for conventional induction hardening or carburizing grades. TSH steels have significantly less alloying elements such as manganese, molybdenum, chromium and nickel, making them less expensive than the majority of conventional low alloy steels. Their chemical composition is somewhere between micro-alloy steels and plain carbon steels, providing fine-grain martensite with extremely high compressive stresses at the tooth surface.

With TSH technology, components are usually through-heated at relatively low temperatures sufficient for austenitization or partial heated (depth of heating needs to be 2-3 times deeper than required harden depth) and then are rapidly quenched. The hardened depth is mainly controlled by the steel's chemical composition. Even though components made from TSH steels are often heated through, their limited hardenability allows obtaining crisp hardness case depth with well-controlled hardness pattern having minimum case hardness deviations even when hardening complex-shaped parts (Figs. 7–8).

In the past, it was practically impossible to induction harden components shown in Figs. 6–9. Now it is possible to

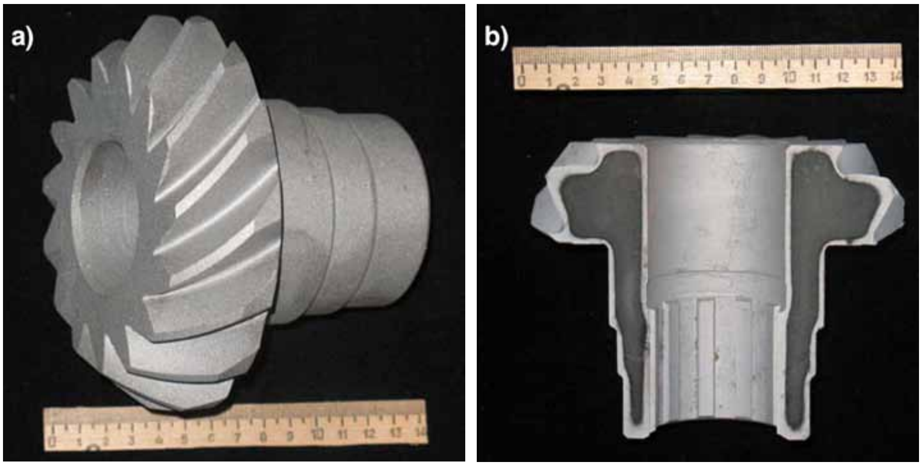

Figure 6 **TSH (through-heating for surface hardening) steel's uninterrupted induction-hardened pattern is obtained on a spiral bevel gear (courtesy ERS Engineering Corp.).**

get those impressive, uninterrupted hardness patterns by using a simple operation: through heating those parts using low frequency inverters and water quenching. Notice that the spiral bevel pinion (Fig. 6) was induction-hardened on OD, ID and teeth region using a single operation having continuous hardness pattern. The carrier pin (Fig. 9) was induction hardened on the outside surface (1.25" diameter) and two inside diameters (longitudinal and transversal) using a single operation that also produced an uninterrupted case hardness pattern. The inside diameter of the longitudinal hole was 0.5"; the inside diameter of the transverse hole was 0.25" (Fig. 7).

Figure 7 Section of induction-hardened transmission gear (courtesy ERS Engineering Corp.).

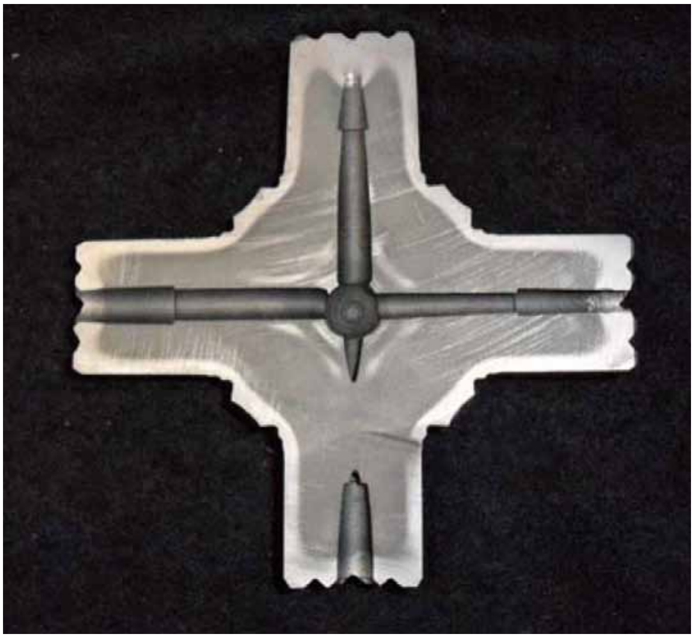

Figure 8 Induction-hardened automotive journal cross section (courtesy ERS Engineering Corp.).

Figure 9 Carrier pin: simultaneous OD- and ID-hardening (courtesy ERS Engineering Corp.).

Conclusions

Induction heat treating being an environmentally friendly, green and lean technology is an increasingly popular choice for induction-hardening of gears and gear-like components.

Recently developed inverters and process know-how further expand its capabilities.

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Dr. Valery Rudnev is group director/science and technology, for Inductoheat Inc., an Inductotherm Group Company. A Fellow of the American Society for Materials, he is known internationally as a major voice in the induction heating industry. Rudnev possesses more than 30 years of experience in induction heating, earning within the American Society for Materials and among induction heating professionals the sobriquet, "Professor Induction." His credits include more than 30 patents, inventions and software registrations, as well as more than 180 published engineering/scientific works. Rudnev in 2003 co-authored the *Handbook of Induction Heating,* and has contributed six chapters for several other publications devoted to various aspects of induction heating, induction heat treating, computer modeling and mathematical simulations.