

Single-coil dual-frequency induction hardening of gears

Induction Hardening of Gears

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.

In recent years, gear manufacturers have gained additional knowledge about how technology can be used to produce higher quality induction hardened gears and gear-like components with less distortion. The application of this knowledge has resulted in gears that are quieter, lighter, and lower cost with an increased load-carrying capacity to handle higher speeds and torques, while generating a minimum amount of heat and requiring minimum or no post grinding.

Steels containing 0.40 to 0.60% carbon content are commonly specified for induction hardening of gears^[1-3]; for example, AISI 1045, 1552, 4140, 4150, 4340, and 5150. In some cases, steels with high carbon content are used (e.g., 52100). Depending on the application, tooth hardness after tempering typically is in the 48 to 60 HRC range.

Gear Spin Hardening (Encircling Inductors)

Spin hardening is the most popular approach for hardening gears having 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^[1].

When applying encircling coils, it is possible to obtain substantially different hardness patterns by varying process parameters. Figure 1 illustrates a diversity of induction hardening patterns that were obtained with variations in frequency, heat time, and coil power^[1].

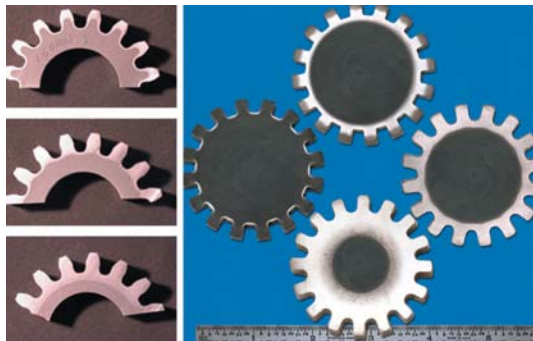


Fig. 1 — Variety of induction hardening patterns obtained using variations in frequency, heat time, and coil power.

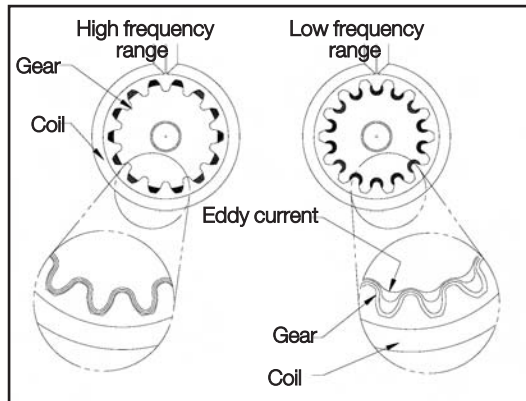


Fig. 2 — Frequency influence on eddy current flow within the gear when using an encircling coil^[1].

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 (Fig. 2). 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.

Quite often, to prevent problems such as pitting, spalling, tooth fatigue, and endurance, it is required to harden the contour of the gear, or to have gear-contour hardening (Fig. 3). This often maximizes beneficial compressive stresses within the case depth and minimizes distortion of as-hardened gears.

In some cases, obtaining a true contour hardened pattern can be a challenging task due to the difference in current density (heat source) distribution and heat transfer conditions within a gear tooth. Two main factors must be optimized to obtain the contour hardness profile.



Fig. 3 — Contour hardened gears.



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. He has 28 years of experience in induction heating. His expertise is in materials science, metallurgy, electromagnetics, heat treating, computer modeling, and process development. Credits include 21 patents and 154 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; www.inductoheat.com.

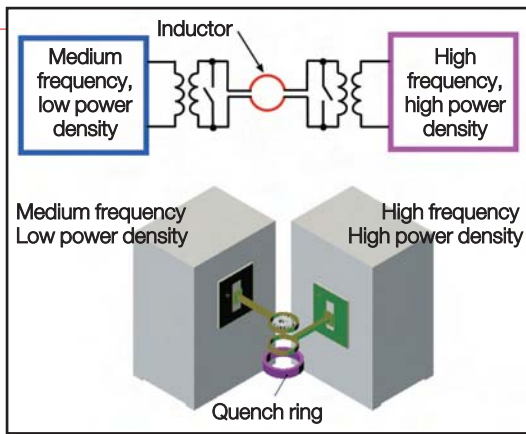


Fig. 4 — Conventional dual-frequency induction hardening using a single inductor (top) and two inductors (bottom).

The first factor is that with encircling-type coils, the root area does not have as good electromagnetic coupling with the inductor compared with the coupling at the gear tip. Therefore, it is more difficult to induce energy into the gear root. Secondly, there is a significant heat sink located under the gear root (below the base circle).

Traditional Gear Hardening Techniques

The power pulsing single-frequency concept was developed as the first step in overcoming difficulties in obtaining contour-like hardness pattern^[1-3]. Power pulsing provides the desirable heat flow toward the root of the gear without appreciably overheating the tooth tip, enabling the attainment of the desired metallurgical structures and helping to obtain gear contour-like hardness pattern. Depending on the application, preheat can consist of several stages (preheat power pulses). Obviously, preheating reduces the amount of energy required in the final heat.

After preheating, there might be a soak time ranging from two to ten seconds to achieve a more uniform temperature distribution across the teeth of the gear. Final heat times can range from less than

one second to several seconds. The power pulsing dual-frequency concept is a further improvement in the attempt to obtain a true contour hardness pattern and to minimize gear distortion. Two different power supplies are required. The idea of using two different frequencies to produce the desired contour-like pattern has been around since the late 1950s. Since then, several companies have pursued this idea, and different names and abbreviations have been used to describe it. Inductoheat built its first contour-hardening machine that applied a dual frequency concept in 1986. Since that time, the process has been refined. However, regardless of the differences in process recipes, the basic idea remains the same.

The gear is induction preheated to a temperature determined by the process features, typically being 350 to 100°C below the critical temperature A_{c1} . The preheat temperature depends on the type and size of the gear, tooth shape, prior microstructure, required hardness pattern, acceptable distortion, and the available power source. Usually, preheating is accomplished by using medium frequency (3 to 10 kHz). Lower frequency results in greater eddy current penetration depths, which lead to more "in-depth" preheating effect. A high frequency (30 to 450 kHz) and high power density are applied during the final heating stage.

Depending on the application, a single-coil design or two-coil arrangement (Fig. 4 top and bottom, respectively) can be used. A single-coil design has many limitations. Some of them are related to

low reliability and maintainability of induction coil. With the second-coil arrangement, one coil provides preheating, and another coil final heating. Both coils work simultaneously if the scanning mode is applied. In the case of a single-shot mode, a two-step index-type approach is used (Fig. 4, bottom).

In some cases, dual-frequency machines produce parts having lower distortion and having more favorable distribution of residual stresses compared with using single-frequency techniques. However, depending on tooth geometry, the time delay between low-frequency preheating and high-frequency final heating could have a detrimental negative effect for obtaining truly contour hardened patterns or in many cases, is not capable of minimizing distortion.

Single-coil Dual Frequency Hardening

Some induction practitioners have heard about simultaneous dual frequency gear hardening, which uses two single-frequency inverters working on the same coil at the same time. Low frequency helps to austenitize the roots of the teeth and high frequency helps to austenitize the teeth flanks and tips.

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

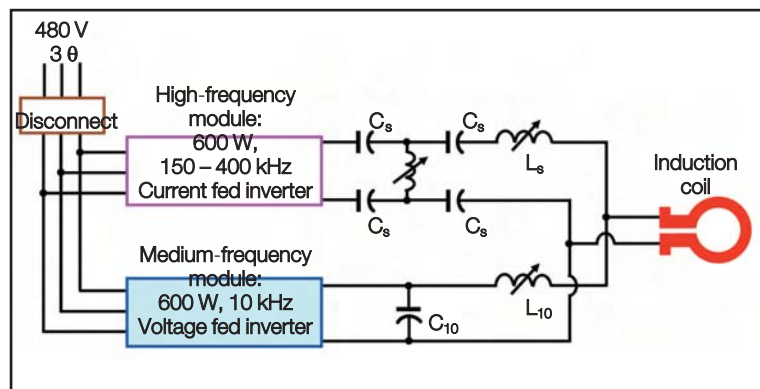


Fig. 5 — Sketch of the circuitry of single-coil dual frequency inverter.

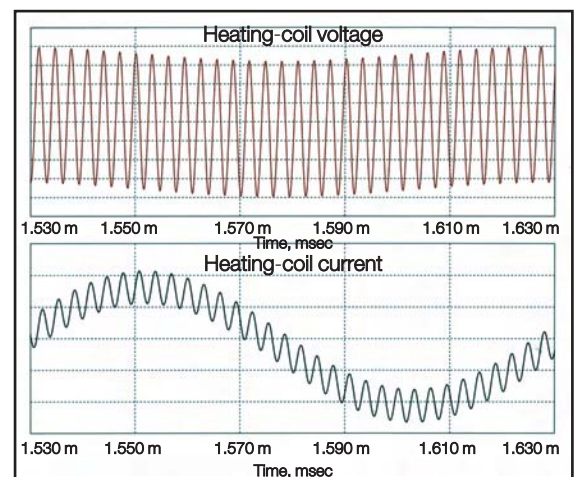


Fig. 6 — Wave forms of coil current and coil voltage of a single-coil dual frequency hardening technology.

For example, Inductoheat has recently shipped a single-coil dual frequency induction gear hardening system to a leading supplier of automotive engine and powertrain components. Figure 5 shows a sketch of the circuitry of the new Inductoheat gear-hardening system. Figure 6 shows wave-forms of coil current and coil voltage when two appreciably different frequencies are applied at the same time to a single inductor. This machine was designed specifically for induction hardening of internal wide-face, gear-like component having a minor gear diameter of 6.9 in. (176 mm) and a major gear diameter of 7.3 in. (186 mm) using a single-shot heating mode.

The total power exceeds 1,200 kW comprising medium-frequency (10 kHz) and high-frequency (120 to 400 kHz) modules working not just simultaneously, but in any sequence desirable to optimize properties of the gears heat-treated using this unique technology. Total heat time was minimized to about 1.5 second. At the beginning of heating cycle, a medium fre-

quency is applied for about 0.8 s providing the required root heating. For the remainder of the heat cycle, two frequencies were working together complementing each other.

Inductoheat's two-frequency induction gear-hardening system (Fig.7) also has some "auto-match" items to simplify tuning. It is rugged and will 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.

Lastly, recently patented Inductoheat IFF (independent frequency and power control) technology provided an opportunity for using the variable frequency approach for tailoring the hardening pattern per gear geometry.

HTP

References

1. V. Rudnev, D. Loveless, R. Cook, and M. Black, *Handbook of Induction Heating*, Marcel Dekker, 2003.
2. V. Rudnev, Induction hardening of gears and critical components, Part 1., *Gear Technology*,



Fig. 7 — Inductoheat's single-coil dual frequency system 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; total power exceeds 1,200 kW.

p 58-63, Sept./Oct. 2008.

3. V. Rudnev, Induction hardening of gears and critical components, Part 2., *Gear Technology*, p 47-53, Nov./Dec. 2008.