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Induction Hardening of Gears: a Review

V. RUDNEV, D. LOVELESS, R. COOK and M. BLACK **Inductoheat Inc., USA**

Extracted from the authors' new book on induction heating, this comprehensive overview of gear hardening concludes by examining spin hardening with encircling inductors.*

Part 2

Gear Spin Hardening (Encircling Inductors)

Spin hardening of gears utilises a single or multi-turn inductor that encircles the part and requires gear rotation. It is used typically for gears with fine- and medium-sized teeth and is considered less time-consuming and more cost-effective than the previously-discussed processes. Therefore, the use of spin hardening is strongly recommended whenever it is possible. Unfortunately, spin hardening is not a cure-all and sometimes cannot be used easily for medium-sized helical and bevel gears and large-module gears, due to an enormously-large amount of required power and difficulties in obtaining the desired hardness pattern.

Gears are rotated during heating to ensure an even distribution of energy across their perimeter. Rotation rates are chosen to suit process requirements.

When applying encircling coils, there are five parameters that play a dominant role in obtaining the required hardness pattern: frequency, power, cycle time, coil geometry and quenching conditions. Proper control of these parameters can result in totally different hardened profiles.

Fig. 12 illustrates a diversity of induction hardening patterns that were obtained on the same carbon steel shaft with variations in time, frequency and power. As a basic rule, when it is necessary to harden the tooth tips only, a higher frequency and high power density should be applied (*Fig.4a*). When hardening the tooth root, a lower frequency and lower power density should be employed (*Fig.4b*). A high power density generally gives a shallow pattern; conversely, a low power density will produce a deep pattern.

In addition to the process parameters mentioned above, hardness pattern uniformity and repeatability depend strongly upon the relative positioning of gear and coil and the ability to maintain gear concentricity within the induction coil.

There are several ways to accomplish quenching in spin hardening of gears. One technique is to submerge the gear in a quenching tank. This is applicable for large-size gears. Gears of small and medium size are usually quenched in

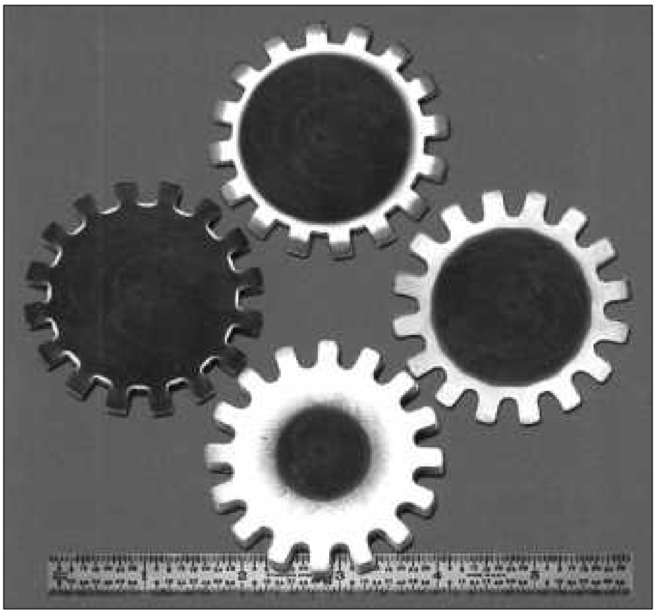

Fig.12. Diversity of induction hardening patterns, with variations in time, frequency and power. (Courtesy of J. LaMonte, Inductoheat Inc.).

**This is an edited version of a section from "Handbook of Induction Heating", the new publication from Marcel Dekker (www.dekker.com), which is reviewed on pages 78-79 of the 2003.3 issue of HEAT TREATMENT OF METALS. Full details about the book appear on page v in this issue. The publisher's kind permission to feature this extract here is gratefully acknowledged.*

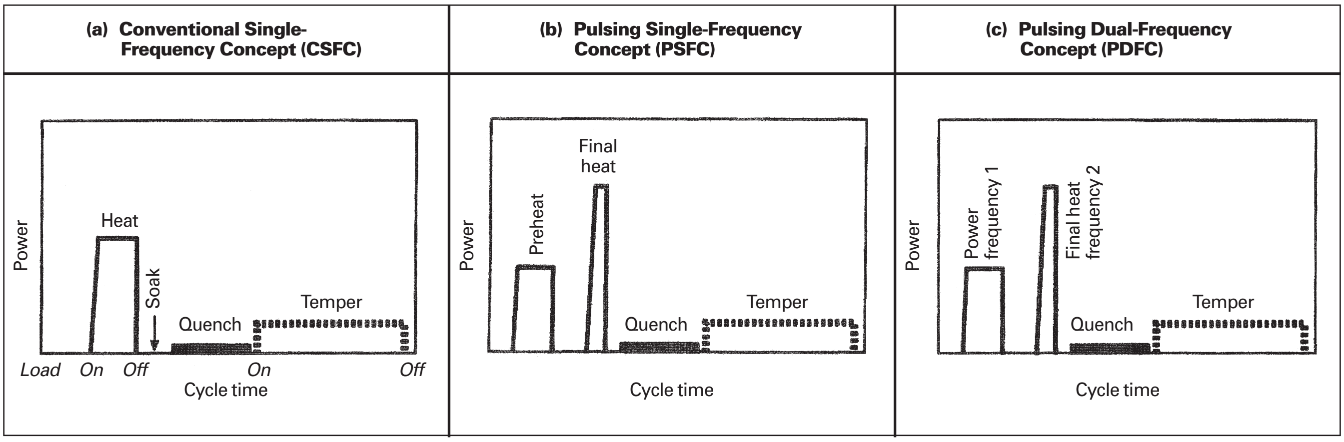

Fig.13. Concepts of gear hardening by induction.

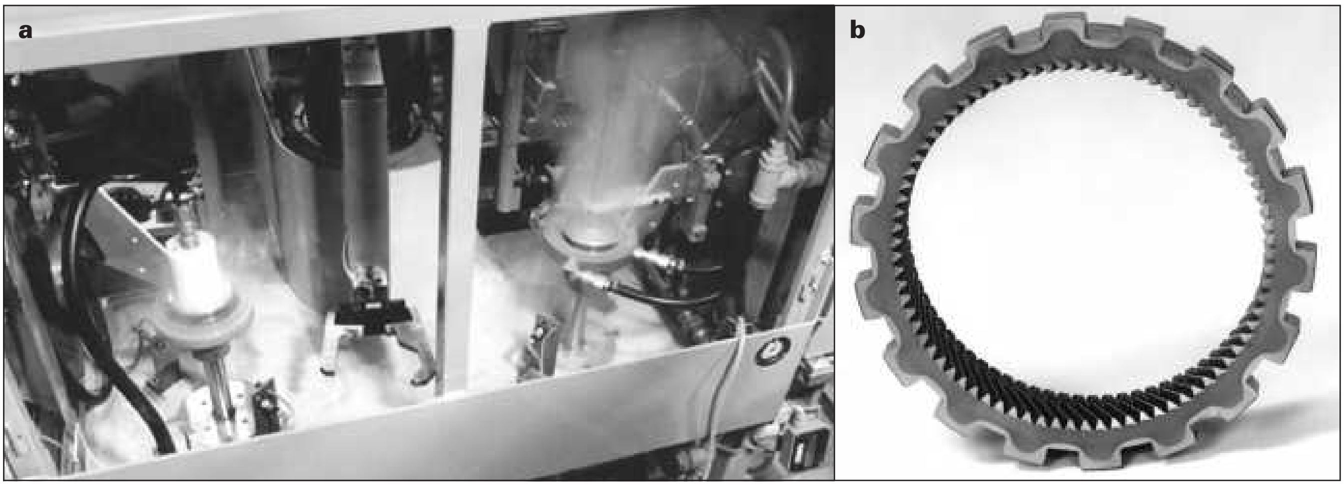

Fig.14. (a) Equipment used to harden OD and ID of gears such as that in (b). (Courtesy of Inductoheat Inc.).

place, using an integrated quench. A third technique requires the use of a separate concentric quench block (quench ring) located below the inductor.

It has been reported[11,14] that more favourable compressive stresses within the tooth root were achieved with the gear spin hardening technique than with the tooth-by-tooth or gap-by-gap methods.

Fig.13 shows three of the most popular design approaches for induction gear heat treating processes that employ encircling-type coils: conventional single-frequency concept (CSFC); pulsing single-frequency concept (PSFC); and pulsing dual-frequency concept (PDFC). All three can be used in either a single-shot or scanning mode.

Conventional Single-Frequency Concept (CSFC)

The conventional single-frequency concept[1,7] is used for hardening gears with medium and small teeth. As seen in *Fig.3* (*patterns B* and *E*), the teeth are often through-hardened. Quite frequently, CSFC can also be used successfully for medium-size gears.

As an example, *Fig.14a* shows an induction gear hardening machine that applies this approach. The gear being heat treated in this application is an automotive transmission component with helical teeth on the inside diameter (ID) and large teeth on the outside diameter (OD) for a parking brake. Both the inside and outside diameters require hardening *(Fig.14b).* The hardening of the ID gear teeth requires a higher frequency than the OD. Therefore a frequency of 10kHz was chosen for OD heating and 200kHz was selected for ID heating. Subsequently, quenchant is applied to the hot gear in place; that is, no repositioning is required. This practically instantaneous quench provides a consistent metallurgical response. During quenching, there is minimal or no rotation to ensure that the quenchant penetrates all areas of the gear evenly.

With the equipment in *Fig.14a*, gears conveyed to the machine are transferred by a cam-operated robot to the heat-treating station. Parts are monitored at each station and accepted or rejected based on all the major factors that affect hardened gear quality. These include energy input into the part, quench flow rate, temperature, quench pressure and heat time. An advanced control/monitoring system verifies all machine settings to provide confidence in the quality of processing for each individual gear. Precise control of the hardening operations, and careful attention to the coil design, minimise part distortion and provide the desirable residual stresses in the finished gear. The hardened gear is inspected and moved to the next operation.

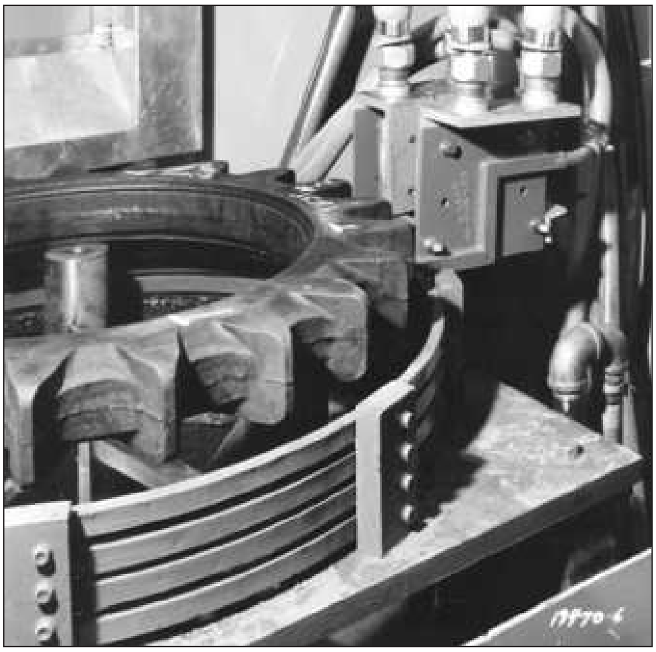

Fig.15. Induction equipment for hardening large gears. (Courtesy of Inductoheat Inc.).

Although CSFC is most suitable for small- and medium-size gears, there are cases when this concept can also be used successfully for large gears. For example, *Fig. 15* shows an induction machine where a multi-turn encircling inductor is used for hardening gears with a major diameter of 701mm, root diameter 617mm and thickness 79mm. In this particular case, it was in the user's best interest to harden and temper in the same coil using the same power supply. In other cases, this might not be the best solution.

In order to prevent problems, such as pitting, spalling, tooth fatigue and poor endurance, hardening of the contour of the gear (contour hardening) is quite often required. In some cases, this can be a difficult task due to the difference in current density (heat source) distribution and heat-transfer conditions within a gear tooth.

Two main factors complicate the task of obtaining the required contour-hardened profile. With encircling-type coils, the root area does not have good coupling with the inductor compared with that at the gear tip. Therefore, it is more difficult to induce energy into the gear root. In addition, there is a significant heat sink located under the gear root (below the base circle, *Fig.4*).

Pulsing Single-Frequency Concept (PSFC)

In order to overcome these difficulties, and to be able to meet customer specifications, the pulsing single-frequency concept was developed *(Fig.13b).* In many cases, PSFC allows the user to avoid the shortcomings of CSFC and obtain a contour hardening profile. Pulsing provides the desirable heat flow toward the root of the gear without noticeable overheating of the tooth tip. A well-defined crisp hardened profile that follows the gear contour (*patterns F* and *G* in *Fig.3*) can be obtained using high power density at the final heating stage.

A typical "dual-pulse" contour hardening system, which applies a pulsing single-frequency concept, has been discussed[1,15,16]. This machine is designed to provide gear contour heat treatment (including preheating, final heating, quenching and tempering) with the same coil, using one high-frequency power supply. *Fig.13b* illustrates the process cycle with moderate-power preheat, soaking stage, short high-power final heat and quench, followed by low-power heat for temper.

Preheating ensures a reasonable heated depth at the roots of the gear, enabling the attainment of the desired metallurgical result and decreasing the distortion in some materials. Preheat times are typically from several seconds to a minute, depending on the size and shape of the gear. Obviously, preheating reduces the amount of energy required in the final heat.

After preheating, there might be a soak time, ranging from 2 to 10 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.

As a general rule, for both CSFC and PSFC techniques, the higher frequency is called for by finer-pitch gears, which typically require a shallower case depth. *Fig.16a* shows a unitised induction hardening system, capable of providing both CSFC and PSFC gear hardening, and *Fig.16b* illustrates a double sprocket hardened therein.

Pulsing Dual-Frequency Concept (PDFC)

A third approach, the pulsing dual-frequency concept, is not new. The idea of using two different frequencies to produce the desired contour pattern has been around since the late 1950s. It was developed primarily to obtain a contour hardening profile for helical and straight spur gears. Several companies, including Contour Hardening, Inductoheat Inc. and others, have pursued this idea, and several different names and abbreviations have been used to describe it[1,13,17,18]. Inductoheat built its first prototype contour hardening machine applying a dual-frequency concept in 1986. Obviously, since that time, the process has been refined and several innovations developed. However, regardless of the differences in nomenclature and the slight process variations, the basic idea is the same.

According to PDFC *(Fig.13c)*, the gear is preheated within an induction coil to a temperature determined by the process features. This temperature is usually 350 to 100°C below the critical temperature A_{c1}. Preheat temperature depends upon the type and size of the gear, tooth shape, prior microstructure, required hardness pattern, acceptable distortion and the available power source. It should be mentioned that the higher the preheat temperature, the lower the power required for the final heat. However, high preheat temperatures can result in increased distortion.

As in previous gear spin hardening concepts, PDFC can be accomplished using a single-shot mode or scanning mode. The scanning mode is typically applied for longer gears.

Preheating is usually accomplished by using a medium frequency (3 to 10kHz). Depending on the type of gear, its size and material, a high frequency (30 to 450kHz) and high power density are applied during the final heat stage. The selected frequency for final heating allows the current to penetrate only to the desired depth. This process gives excellent repeatability.

Depending upon the application, two coil design

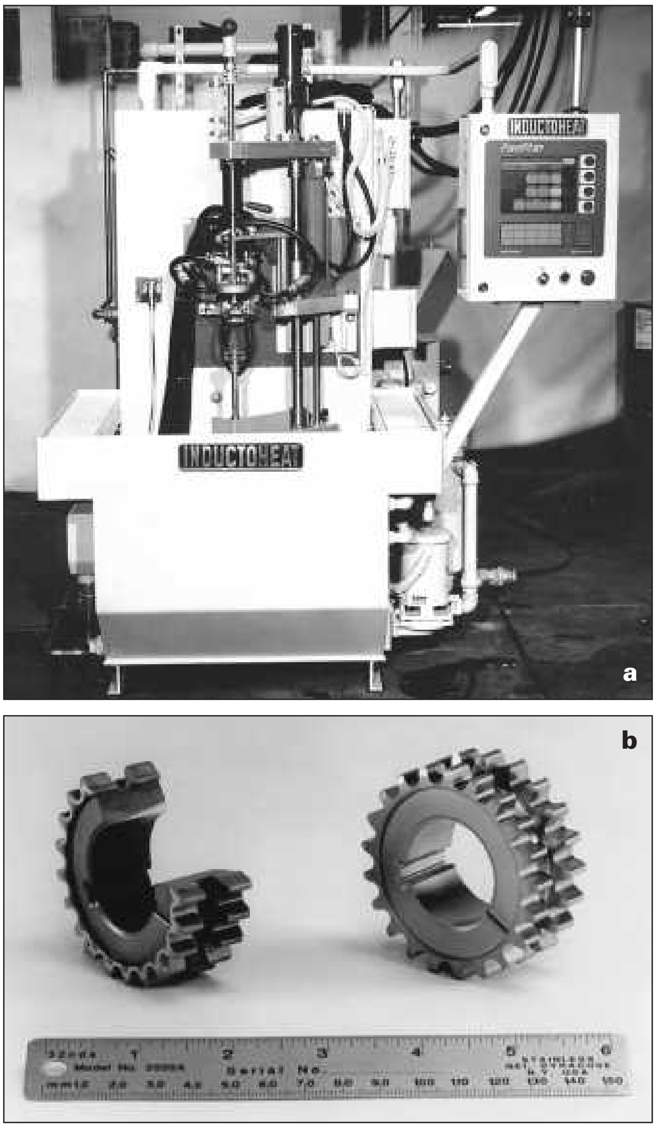

Fig.16. A unitised induction system (a), capable of providing both CSFC and PSFC gear hardening, is used to harden the double sprocket shown in (b).

arrangements can be used when applying the scanning or single-shot modes. In the first arrangement (*Fig.17*), one coil and two power supplies are utilised to harden the gear. The sequence of operations is as follows:

(1) location of the gear within the induction coil;
(2) beginning of gear rotation;
(3) low-frequency voltage is applied to the induction coil;
(4) the coil begins to move along the gear length and preheats the full length of the gear;
(5) after completion of the preheating stage, the coil is disconnected from the low-frequency source;
(6) upon returning to the initial position, a high-frequency voltage is applied to the coil and a second scanning cycle begins;
(7) the gear is heated to the hardening temperature and quenching is applied simultaneously, or the gear is quenched after completion of the heating stage.

This first approach has many limitations, including low

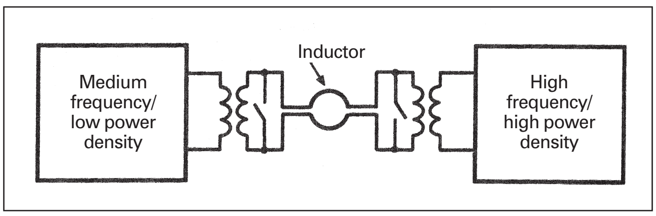

Fig.17. Using one coil and two inverters for PDFC gear hardening.

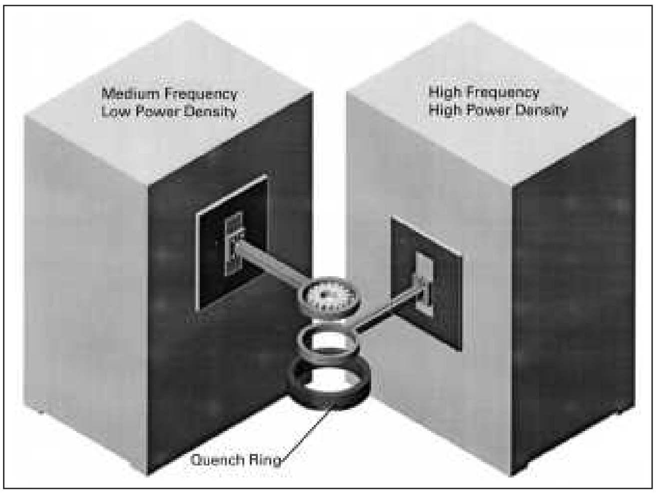

Fig.18. One coil is used for preheat and a second is for final heat in the common approach to PDFC hardening.

Fig.19. 100mm-diameter spur gear contour hardened using PDFC. (Courtesy of Inductoheat Inc.).

reliability and complexity. Therefore, in a great majority of cases, the PDFC process employs a second coil arrangement *(Fig.18)* where two coils and two power supplies are utilised. One coil provides preheating and the second 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.

Quenching completes the hardening process and brings the gear down to ambient temperature. In some cases, dual-frequency machines produce parts with lower distortion and a more favourable distribution of residual stresses than other techniques.

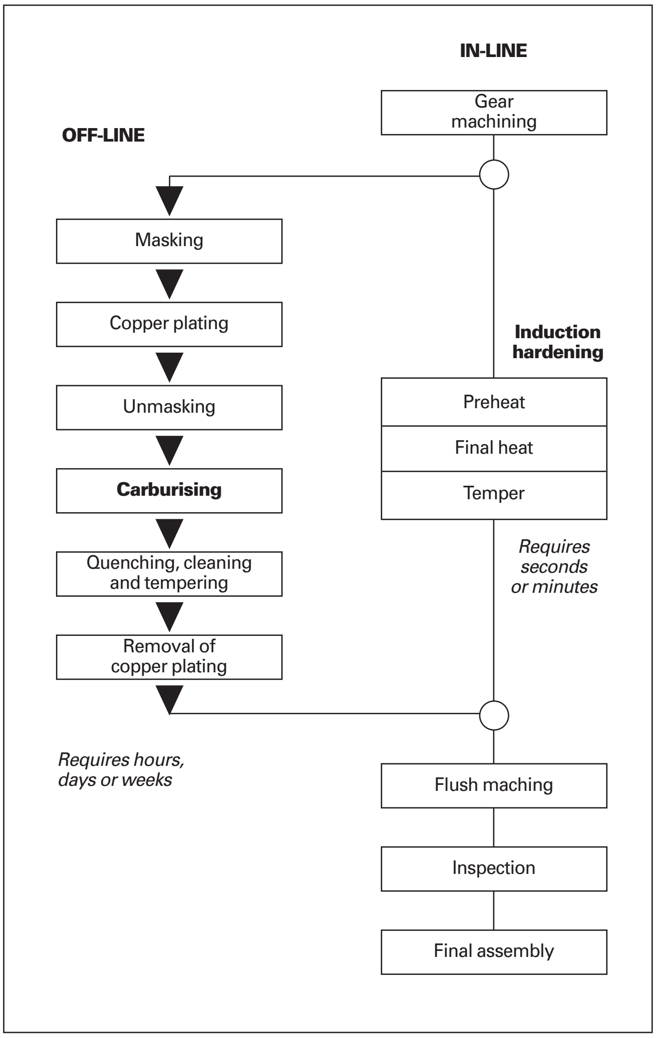

Fig.20. Steps required for carburising compared with those for induction hardening[18]*.*

As mentioned above, when applying high frequency (i.e., 70kHz and higher), it is important to pay special attention to gears with sharp corners. Due to the electromagnetic edge effect, high frequency has a tendency to overheat sharp edges and corners. This results in weakened teeth due to decarburisation, oxidation, grain growth and, sometimes, even local melting of sharp edges. Therefore, in order to improve the life of a gear, the sharp edges and corners should be broken and generously chamfered.

The main drawbacks of the PDFC process are its complexity and high cost, as it is necessary to employ two different power supplies. In some cases, it is possible to use one dual-frequency power supply instead of two single-frequency inverters; however, the cost of these variable-frequency devices is high and their reliability is low.

A 100mm-diameter spur gear induction contour hardened using the PDFC approach is shown in *Fig.19*. As seen from *Fig.3 (pattern G),* the hardness pattern is quite similar to that obtained after carburising. However, the induction contour hardening process is accomplished in a much shorter time, with a much simpler processing procedure. *Fig. 20* shows a comparison of processing steps required for induction heat treating versus carburising[1,17-19].

OTHER ASPECTS

Lightening Holes

Gears are often produced with holes to reduce their weight. In induction hardening of gears with internal lightening holes, including hubless spur gears and sprockets, cracks can develop below the case depth in the inter-hole areas *(Fig.21).* This crack development results from an unfavourable stress distribution during or after quenching. Proper material selection, improved quenching technique, and modifications in gear design and/or required hardness pattern can prevent crack development in the lightening-hole areas.

Powdered Metal Gears

Special attention should be paid when designing induction hardening machines for PM gears. These are affected to a much larger extent by variations in the material properties of sintered metals as compared with gears made by casting or forming. This is because the electrical resistivity, thermal conductivity and magnetic permeability strongly depend on the density of the sintered metal. Variations in the porosity of the PM steel lead to scattered hardness, case depth and residual stresses data.

TSH Technology for Gear Hardening

Impressive results can be achieved not only by developing a sophisticated process, but also by using existing processes in combination with advanced steels. Through and surface hardening (TSH) technology is a synergistic combination of advanced steels and special induction hardening techniques[20]. These new low-alloyed carbon steels, invented by Dr. K. Shepelyakovskii[20] and distributed by ERS Engineering[21], are characterised by very little grain growth during heating into the hardening temperature range. They can be substituted for more expensive standard steels that are typically hardened by conventional induction or carburising.

The main features of TSH technology include the following:

- TSH steels are relatively inexpensive, incorporating significantly smaller amounts (3 to 8 times less) of alloying elements such as manganese, molybdenum, chromium, and/or nickel.
- They require a lower induction hardening frequency (1 to 10kHz), which reduces power supply cost.
- They exhibit high surface compressive residual stresses (up to 600MPa).
- The hardened depth is primarily controlled by the steel's chemical composition and initial microstructure. This makes the heat treating process repeatable and robust.
- They exhibit fine grain size (see *Fig.22*).
- The chance of overheating part edges and sharp corners due to the end effect is reduced.

Fig.23 shows an induction heat-treated gear made from TSH steel. One of the unique features is that, instead of using a two-step approach (first OD heat and then ID heat or vice versa), the gear has been heated and quenched in a single step, using only one inductor. OD and ID teeth have a fine-grained martensite case with a hardness of 62HRC. The microstructure of the core is a combination of very fine pearlite and bainite, with a hardness of 30 to 40HRC.

TSH technology gears are stronger and more durable than some made from conventionally heat-treated standard steels. Typical applications include gears, bushings, shafts, bearings and coil and leaf springs[20,22].

Fig.21. Holes in gears can cause unfavourable stress when induction hardening, resulting in cracks. Material selection and quench are important to reduce risk.

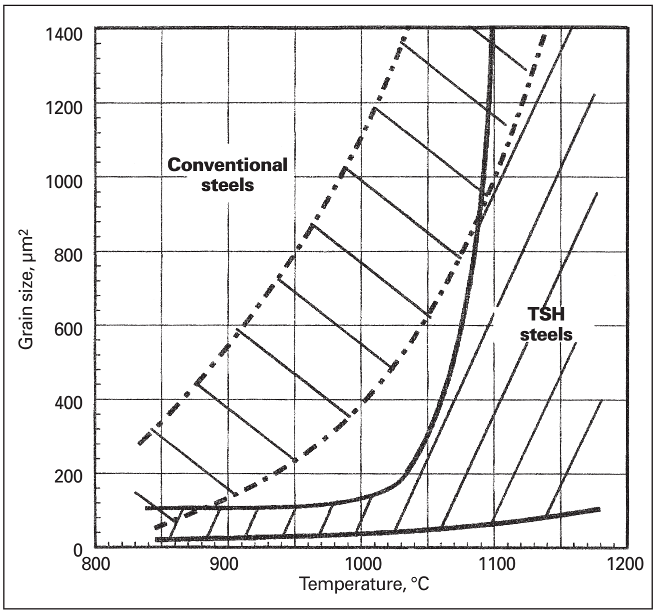

Fig.22. Grain growth for TSH steels versus that of conventional grades[20].

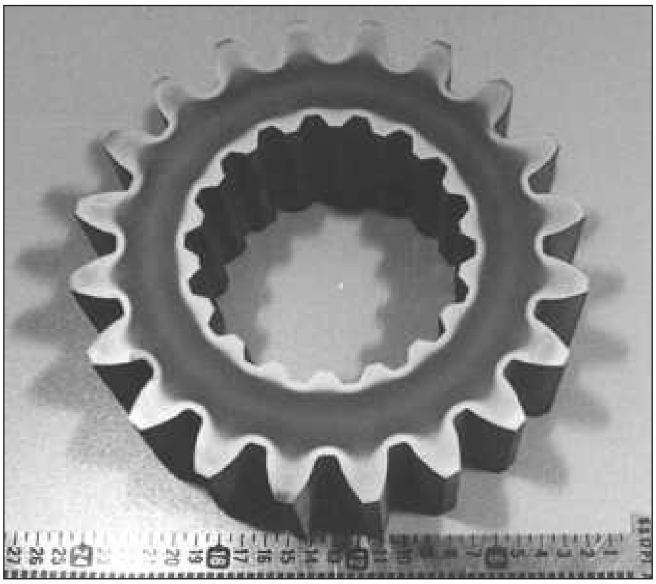

Fig.23. Induction heat-treated gear made from TSH steel.

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AUTHORS' ADDRESS

Dr Valery Rudnev (e-mail: rudnev@inductoheat.com) and his co-authors are with Inductoheat Group, 32251 North Avis Drive, Madison Heights, Michigan 48071, USA.