

Induction Hardening of Gears: a Review

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Extracted from the authors' new book on induction heating, this comprehensive overview of gear hardening includes sections on material selection, hardness patterns, coil design and heating modes.*

Part 1

INTRODUCTION

In recent years, gear manufacturers have increased their technological knowledge of the production of quality gears. This knowledge has led to many improvements, including lower noise, lighter weight and lower cost, as well as increased load-carrying capacity to handle higher speeds and torque with a minimum amount of generated heat. This review concentrates on the role of induction hardening of gears and pinions in achieving these advances.

Not all gears and pinions are well suited for induction hardening. External spur and helical gears, worm gears, and internal gears, racks and sprockets are among the parts that are typically induction hardened (*Fig.1*). Conversely, bevel gears, hypoid gears, and noncircular gears are rarely heat treated by induction.

**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 previous issue of HEAT TREATMENT OF METALS. Full details about the book appear on page vi in this issue. The publisher's kind permission to feature this extract here is gratefully acknowledged.*

In contrast to carburising and nitriding, induction hardening does not require heating of the whole gear. With induction, heating can be precisely localised to the specific areas where metallurgical changes are desired (e.g., flank, root and gear tip can be selectively hardened) and the heating effect on adjacent areas is minimum. Depending upon the application, tooth hardness ranges typically from 42 to 60HRC.

One of the goals of induction gear hardening is to provide a fine-grained fully-martensitic layer on specific areas of the gear to increase hardness and wear resistance, while allowing the remainder of the part to be unaffected by the process. The increase in hardness also improves contact fatigue strength. A combination of increased hardness, wear resistance, and the ability to provide a fine martensite structure, often allows the substitution of inexpensive medium- or high-carbon steel or low-alloyed steel for more expensive highly-alloyed steels.

It is not always possible to obtain a fully-martensitic case. Depending upon the kind of steel, the presence of some retained austenite within the hardened case is unavoidable (unless cryogenic treatment is used). This is particularly true for steels with high carbon content and cast irons.

Up to a certain point, some retained austenite does not noticeably reduce the surface hardness. However, it introduces some ductility and provides better absorption of impact energy, which is imperative for heavily-loaded gears. In addition, having an unstable nature, retained austenite has a tendency, with time, to transform into martensite, adding to compressive residual stresses and increasing the surface hardness. From this perspective, a small amount of retained austenite is not only harmless but may even be considered beneficial in some cases. However,

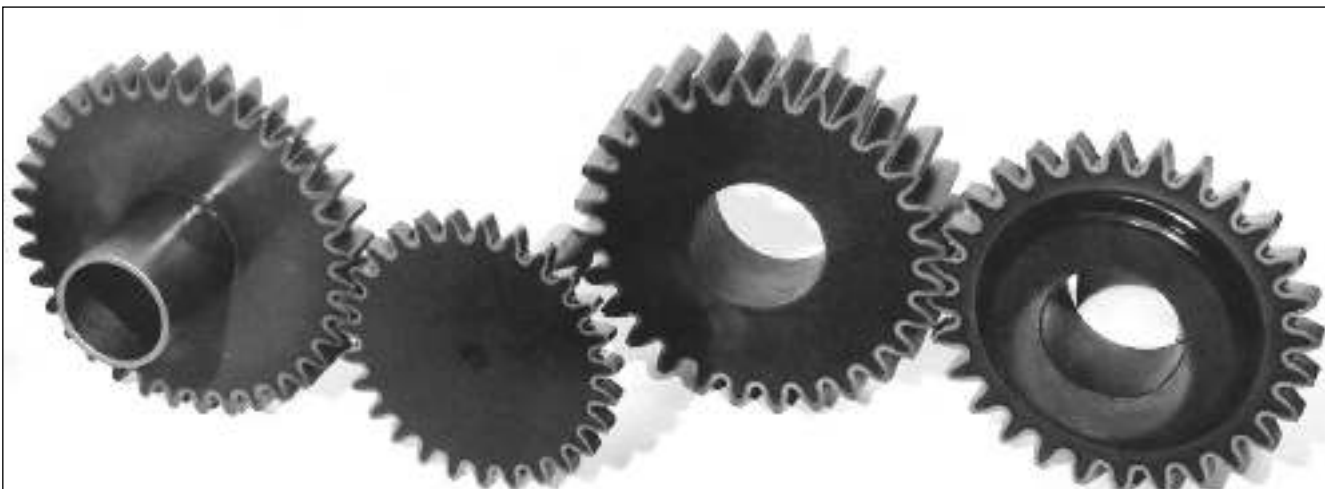


Fig.1. Typical induction-hardened gears.

excessive retained austenite can be detrimental because it may reduce the surface hardness noticeably, weaken bending fatigue properties, and can result in the appearance of a crucial amount of brittle untempered martensite during gear service life.

Another goal of gear induction hardening is the development of significant compressive residual stresses at the gear surface. This is an important feature, since it helps to inhibit crack development as well as resist tensile bending fatigue.

The kind of steel/iron used, its prior microstructure, and gear performance characteristics (including load condition and operating environment) dictate the required surface hardness, core hardness, hardness profile, gear strength, and residual stress distribution.

MATERIAL SELECTION AND REQUIRED GEAR CONDITIONS PRIOR TO HEAT TREATMENT

Steel selection depends upon features of the gear working conditions, required hardness and cost. Low-alloy and medium-carbon steels with 0.4 to 0.55% carbon content (i.e. AISI 4140, 4340, 1045, 4150, 1552, 5150) are quite commonly used for gear heat treatment by induction.

Microstructure

When discussing induction hardening, it is imperative to mention the importance of having "favourable" material conditions prior to gear treatment. Hardness repeatability and the stability of the hardness pattern are grossly affected by the consistency of the microstructure prior to heat treatment (referred to as microstructure of a "green" gear) and the steel's chemical composition¹⁻⁵.

A "favourable" initial microstructure, comprising a homogeneous fine-grained quenched and tempered structure with hardness of 30 to 34HRC, leads to fast and consistent response to induction heat treating, with the smallest shape/size distortion and a minimum amount of grain growth. This type of prior microstructure results in higher hardness and deeper hardened case depth compared with a ferritic/pearlitic initial microstructure.

If the initial microstructure of the gear contains a significant amount of coarse pearlite and, most importantly, coarse

ferrite or clusters of ferrite, then it cannot be considered favourable. Gears with such structures will require longer austenitisation times and/or higher austenising temperatures to make sure that diffusion-type processes are completed and homogeneous austenite is obtained. Ferrite, with less than 0.025% carbon, is practically a pure iron and does not contain the carbon required for martensitic transformation. A long austenitisation time is required for carbon to diffuse into large carbon-poor areas (clusters) of ferrite. Otherwise, clusters of ferrite will be retained in the austenite and, upon quenching, a complex ferritic-martensitic microstructure, with scattered soft and hard spots, will result.

Compared with the quenched-and-tempered prior microstructure, steels with large carbides (i.e., spheroidised microstructures) also exhibit poor response to induction hardening and necessitate prolonged heating and higher temperatures for austenitisation. Longer heat time leads to grain growth, the appearance of coarse martensite, data scatter, an extended transition zone, and gear shape distortion. Coarse martensite has a negative effect on tooth toughness and creates favourable conditions for crack development.

Chemical Composition

As opposed to other heat treating techniques, hardening by induction is appreciably affected by variations in workpiece chemical composition. Therefore, favourable initial material conditions also include tight control of the specified chemical composition of steels and cast irons. Wide compositional limits cause surface hardness and case depth variation. Conversely, tight control of the composition eliminates possible variation of the heat-treat pattern resulting from multiple steel/iron sources. Segregated and banded initial microstructures of "green" gears should be avoided.

Surface Condition

The surface condition of the gear is another factor that can have a distinct effect on gear heat treating practice. Voids, microcracks, notches, and other surface and subsurface discontinuities, as well as other stress concentrators, can initiate crack development during induction hardening when the material goes through the expansion-contraction cycle; thermal gradients and stresses can reach critical values and "open" notches and microcracks. Conversely, a homogeneous structure, with a smooth surface free of voids, cracks, notches and the like, improves the heat treating response, and positively affects important gear characteristics such as bending fatigue strength, endurance limit, gear durability and gear life.

Medium and high frequencies have a tendency to overheat sharp corners; therefore, gear teeth should be generously chamfered if possible for optimum results in the heating process.

Accuracy

Because gears provide transmission of motion and force, they belong to a group of the most geometrically accurate power transmission components. A gear's precision and ability to provide a required fit to its mate greatly affect its performance characteristics. Typical required gear tolerances are measured in microns; therefore the ability to control such undesirable phenomena as gear warpage, ovality, conicality, out-of-flatness, tooth crowning, bending, growth and shrinkage plays a dominant role in providing quality gears.

This is why hardness-pattern consistency, minimum shape/size distortion and distortion repeatability are among the most critical parameters that should be satisfied when heat treating gears.

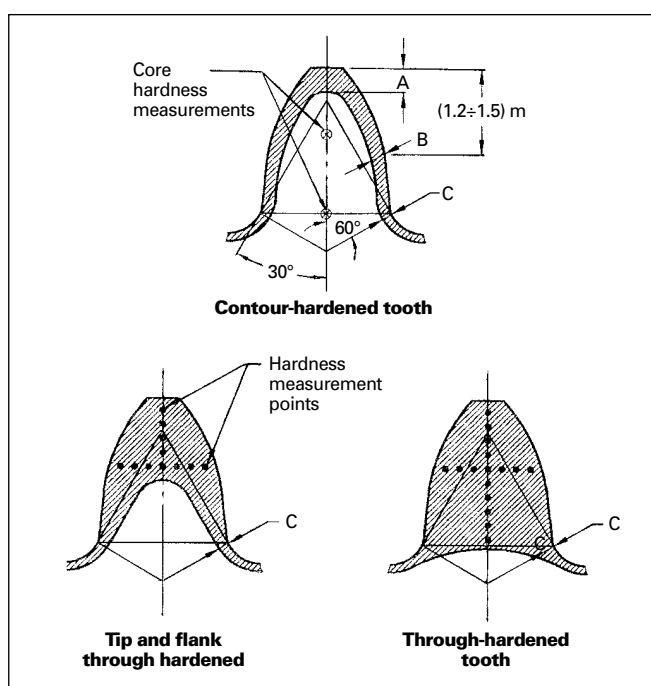


Fig.2. Typical locations of gear profile measurements. Depending on type of gear and its application, specific procedures are created for these measurements.

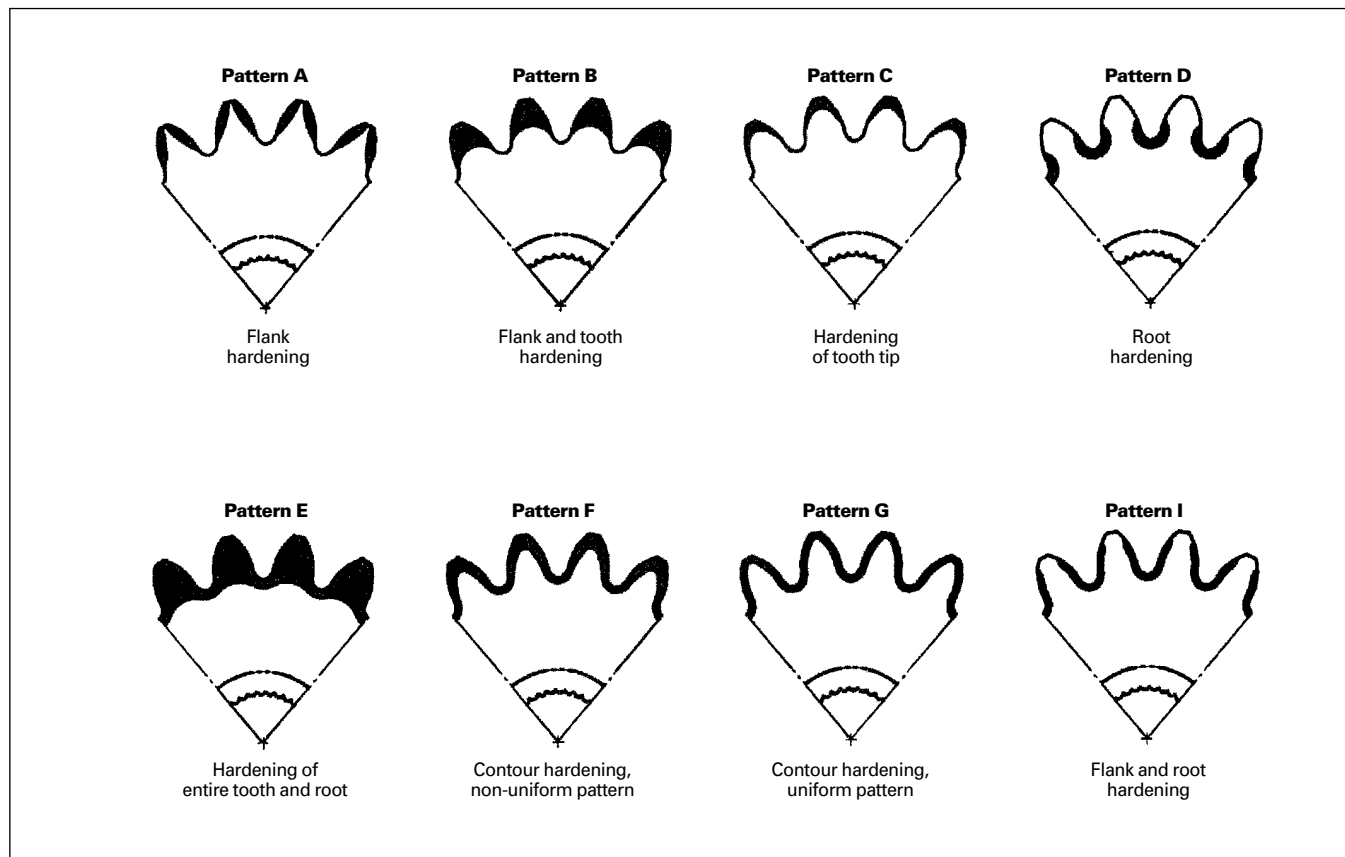


Fig.3. Induction hardening patterns of gears.

OVERVIEW OF HARDNESS PATTERNS

The first step in designing an induction gear heat treatment machine is to specify the required surface hardness and hardness profile. Fig.2 shows typical locations of gear profile measurements. In some cases, depending upon the type of gear and its application, some operators create specific procedures for gear profile measurements.

Insufficient hardness, as well as an interrupted (broken) hardness profile at tooth contact areas, will shorten gear life, due to poor load-carrying capacity, premature wear, tooth bending fatigue, rolling contact fatigue, pitting and spalling. They can even result in some plastic deformation of the teeth.

A though-hardened gear tooth, with a hardness reading exceeding 60HRC, is too brittle and will often experience a premature brittle fracture. Hardened case depth should be adequate (not too large and not too small) to provide the required gear tooth properties.

There is a common misconception that a uniform contour profile is always the best pattern for all gear hardening applications. It is not. In many cases, a certain hardness gradient profile can provide a gear with better performance. Operating load condition (whether there are occasional, intermittent, or continuous loads) has a pronounced effect on the type of gear, tooth geometry and hardness profile. Loads lasting up to 30 minutes per day are considered occasional loads. Loads lasting several minutes per hour are considered to be intermittent-type loads. Continuous loads last from 10 to 24 hours^{2,6}.

Let's briefly evaluate a variety of hardening patterns (Fig.3) and their effect on gear load-carrying capacity and life^{7,8}:

- **Pattern A** is a flank hardening pattern that has been used since the late 1940s for hardening large gears (with teeth modulus of eight and larger). The hardened pattern occupies the tooth flank area and ends prior to the tooth fillet. This provides the required wear resistance, but the typical failure mode of gears with this type of pattern is bending fatigue caused by repeated loading. A crack

typically initiates in the tooth root/fillet area. In the hardened/non-hardened transition region, the residual stresses change from compressive in the hardened area to tensile in the non-hardened area. The maximum tensile residual stresses are located just below the end of the hardened pattern. A combination of applied tensile stresses with tensile residual stresses creates a favourable condition for early crack development in the root/fillet area, particularly for heavily-loaded gears.

Therefore when *pattern A* is imparted, mechanical hardening (i.e., roll or ball hardening) is typically required to harden the fillet area and develop useful compressive residual stresses there that will resist bending fatigue. When mechanical hardening is not employed, use of a pattern that hardens the root areas as well, such as that pictured in *pattern I*, is typically recommended.

- **Pattern B** is a flank and tooth hardening pattern. This pattern has a shortcoming similar to the previous one – a poor load-carrying capacity – yet can be used in cases where wear resistance is of prime concern. *Patterns E, F* and *G* provide better results when a combination of wear, tear and bending fatigue resistance is required.
- **Pattern C** is a tooth-tip hardening pattern. In this case, the gear has minimum shape distortion. In addition, the application of gears with this pattern is extremely limited because the two most important tooth areas (flank and root) are not hardened. Indeed, due to unfavourable residual stress distribution, the bending fatigue strength of a gear with this pattern, as well as *patterns A* and *B*, can even be 25% lower than that of the gear prior to hardening ("green" gear)⁴. In most cases, *patterns F* and *G* would be better choices.
- **Pattern D** is a root hardening pattern. The maximum bending stresses are located in the tooth fillet area; therefore, this pattern provides good fillet/root strengthening, with a combination of hard surface, sufficient case depth and compressive stresses. The root

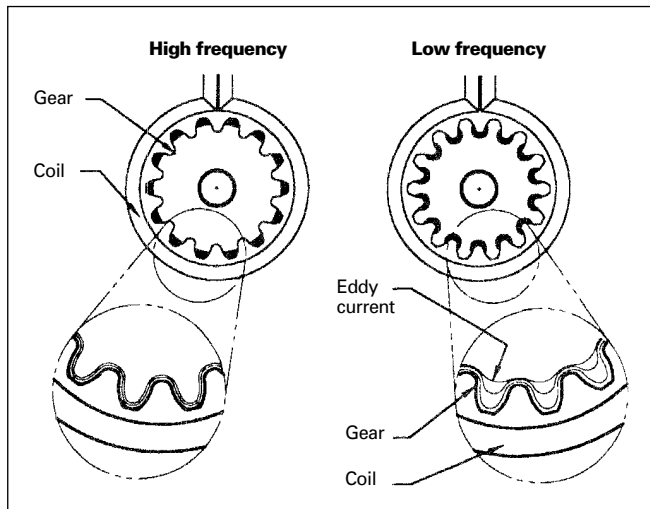


Fig.4. Frequency influence on hardness profile with encircling induction coil: (a) high frequency; (b) low frequency.

is essentially reinforced; thus the maximum tensile residual stresses are shifted far away from the root/fillet surface to a depth where tensile residual stresses will not complement applied tensile stresses during service and create bending fatigue fracture.

However, application of this pattern is quite limited. Since the tooth flank is not hardened, it provides poor wear resistance that may result in removal or displacement of metal particles from the gear surface. Theoretically, it is possible to imagine the necessity of using this pattern as well as the previous one; however, it is more practical to use another, such as *pattern I*.

- *Pattern E* is one of the most common induction hardening patterns, particularly for small-size gears and sprockets. Because the body of the tooth is through-hardened, some quench cracking may occur. In addition, there is danger of brittle fracture in gears with through-hardened teeth, particularly those subjected to shock loads. The core should be able to withstand impact loads and prevent plastic deformation of the gear teeth. It should also have some ductility. This is why low-temperature tempering is often applied. The core strength is measured by its hardness. Low-temperature tempering lowers the final hardness down to 52 to 58HRC and provides some ductility and toughness to the gear teeth. This pattern offers good resistance to wear and pitting.
- *Patterns F and G* are popular patterns for medium-size gears in many applications. According to *pattern F*, the case depth in the tooth root area is typically 30 to 40% of that at the tooth tip. A slightly larger hardened depth at the tooth pitch line, compared with at the root, is beneficial in preventing spalling and pitting. It is very important to harden the entire gear perimeter, including the flank and root area. An uninterrupted hardened pattern on all contact areas of the tooth indicates good wear properties of the gear. It also ensures the existence of uninterrupted distribution of desirable compressive stresses at the gear surface. Because gear teeth are not hardened through, a relatively ductile tooth core (30 to 44HRC) and a hard surface (56 to 62HRC) provide a good combination of important gear properties, such as exceptional wear resistance, toughness and bending strength, and promote superior gear durability.
- *Pattern I* is one of the most popular choices for induction hardening of large gears and pinions (i.e., gears with OD of 300mm and larger) with coarse teeth (modules greater than eight). This pattern provides an exceptional combination of fatigue and wear strength, as well as

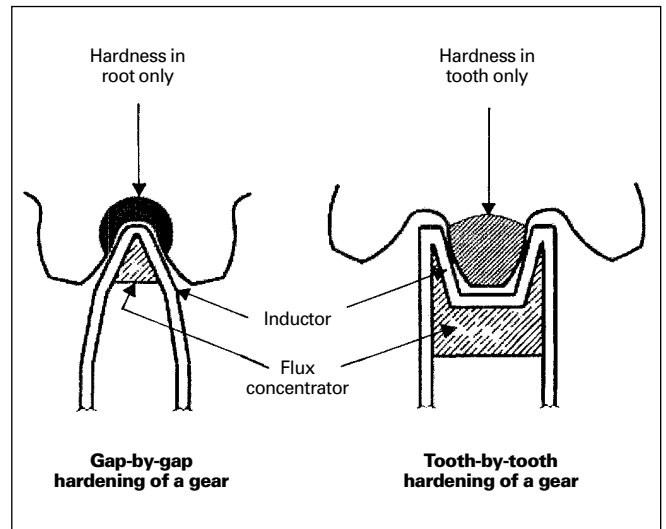


Fig.5. Gap-by-gap and tooth-by-tooth induction hardening.

resistance to shock loading and scuffing (severe adhesion wear where metal particles transfer from one tooth to another). This is very important for heavily-loaded gears and pinions experiencing severe shock loads. It is recommended that, for these applications, surface hardness should not be very high (typically in the range of 55 to 59HRC). If surface hardness exceeds 61 to 62HRC, the gear might be too brittle and could experience some tooth bending failures.

COIL DESIGN AND HEAT MODE

The variety of required hardness profiles calls for different coil designs and heat modes^{1,7-8}. Development is largely based on induction principles, the result of mathematical evaluation and experience with previous jobs. This establishes not only process parameters, including cycle times and power levels, but also coil geometry.

Tooth-by-Tooth and Gap-by-Gap Inductors

Generally, gears are induction heat treated by either encircling the part with a coil (so-called spin hardening, Fig.4) or, for larger gears and pinions, heating them "tooth-by-tooth" or "gap-by-gap" (Fig.5)^{1,2,7-11}.

Tooth-by-tooth and gap-by-gap techniques require a high level of skill, knowledge and experience in order to obtain the required hardness pattern. These techniques can be realised by applying a single-shot or scanning mode. Scanning rates can be quite high, reaching 380mm/minute and even higher. Both tooth-by-tooth and gap-by-gap techniques are typically not very suitable for small and fine-pitch gears (modules smaller than six).

Coil geometry depends upon the shape of the teeth and the required hardness pattern. In the tooth-by-tooth technique, an inductor encircles a single tooth or is located around it. Such an inductor design provides *patterns B and C*.

Gap-by-gap techniques require the coil to be symmetrically located between the flanks of two adjacent teeth. This inductor can be designed to heat only the root and/or flange of the tooth, leaving the tip and tooth core soft, tough and ductile. These are many variations of coil designs applying these principles. Probably one of the most common is the inductor shape shown in Fig.6. This type was originally developed in the 1950s by the British firm Delapena. Fig.7 shows the pattern profile for gap-by-gap induction hardening.

As can be seen from Fig.8, the path of the induced eddy current forms a butterfly-shaped loop. The maximum current density is located in the teeth root area (the entry part of the butterfly). In order to further increase the power

density induced in the root, a magnetic flux concentrator is applied. A stack of laminations, oriented across the gap, or shaped powder-based magnetic materials are typically used as flux concentrators here. (*Magnetic flux concentration, materials selection and general requirements of magnetic concentrators are discussed in detail elsewhere in the book*).

Although the eddy-current path has a butterfly shape, when applied with a scanning mode, 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, which can substantially weaken the tooth.

Gears heat treated by tooth-by-tooth or gap-by-gap processing can be fairly large, having outside diameters of 2.5m or more, and can weigh several tons. These techniques can be applied for external and internal gears and pinions. However, a limitation to hardening internal gears is that the internal diameter typically needs to exceed 200mm and, in some cases, 250mm or more.

Both tooth-by-tooth and gap-by-gap hardening are time-consuming processes with low production rates. Power requirements for these techniques are relatively low and depend upon the production rate, type of steel, case depth, and tooth geometry. Modest power requirements can be considered an advantage because, if spin hardening were used, a large gear would require an enormous amount of power which could diminish the cost-effectiveness of the heat treating process.

Applied frequencies are usually in the range of 1 to 30kHz. However, there are instances where frequencies of 70kHz and even higher have been used. For example, the NATCO submerged technique¹² applied a radio frequency of 450kHz.

Uniformity

Pattern uniformity is quite sensitive to coil positioning. The coil should be located symmetrically in a gap between two teeth. Asymmetrical coil positioning results in a non-uniform hardness pattern. For example, an increase in the air gap between the coil copper and the fillet surface on one side will result in a reduction of hardness and shallower case depth there. Shallow case depth can diminish the bending fatigue strength of the gear. Excessive wear of the working (contacting) side of the gear tooth can also occur.

A decrease of the air gap can result in local overheating or even melting of the gear surface. Some arcing can occur between the coil and the gear surface. Precise coil fabrication techniques, rigidity of the inductor, and careful alignment are required. Special locators should be used to ensure proper inductor positioning in the tooth space. Thermal expansion of metal during heating should be taken into consideration when determining the proper coil-to-gear-tooth air gap.

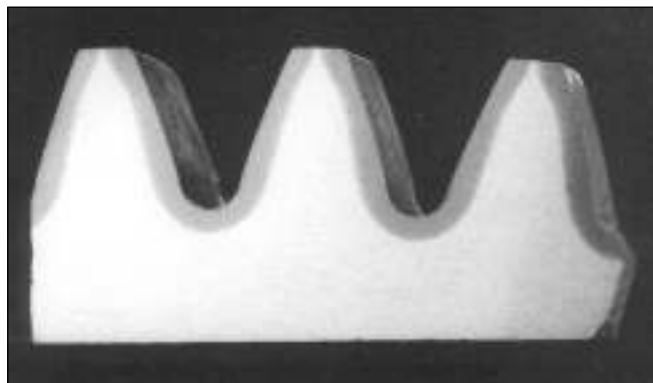


Fig.7. Gap-by-gap pattern profile. (Courtesy of Inductoheat Inc.).

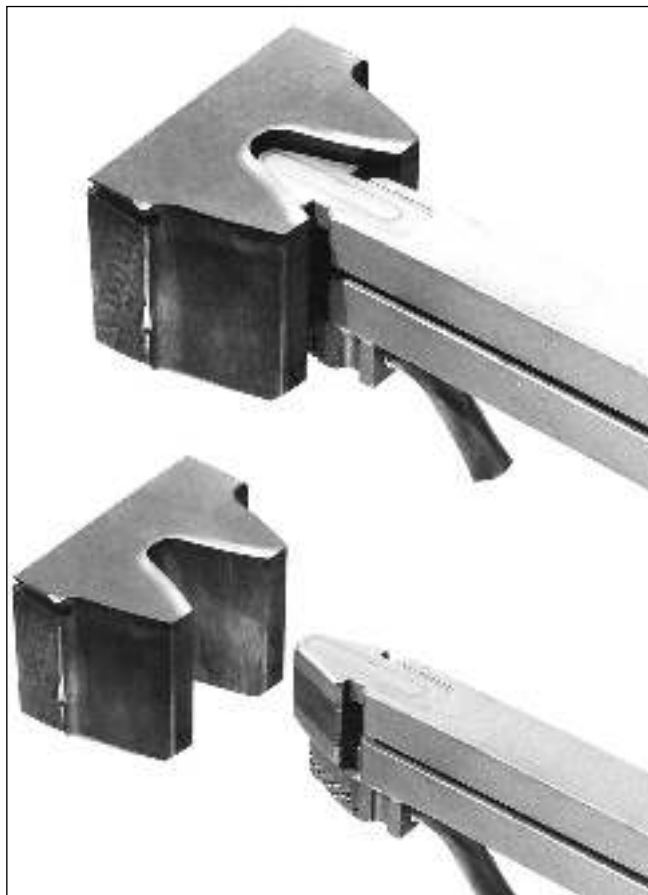


Fig.6. Gap-by-gap inductor and gear. (Courtesy of Inductoheat Inc.).

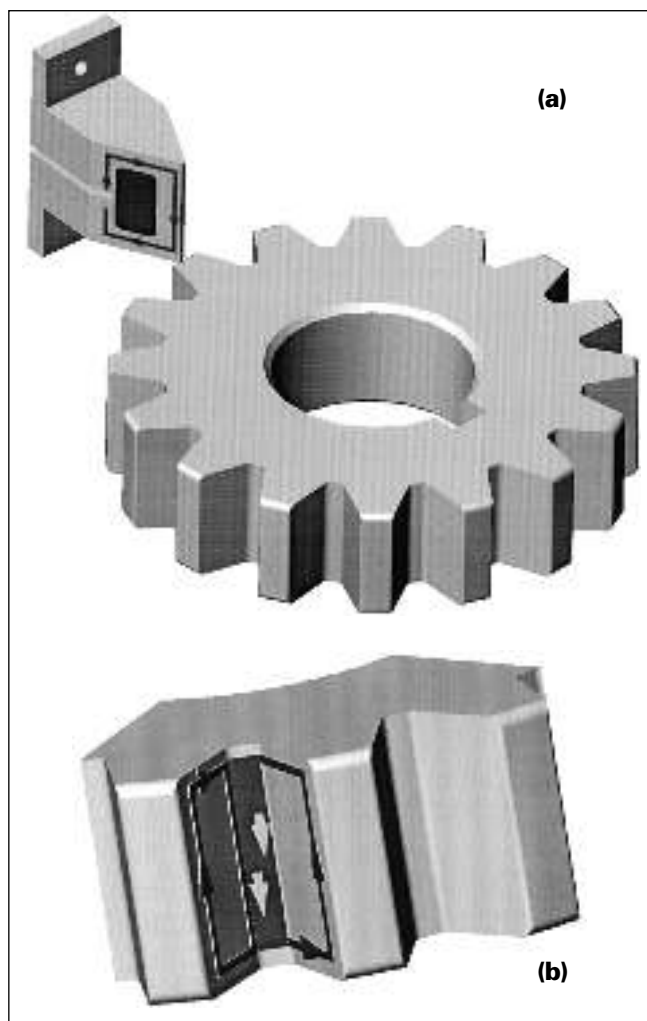


Fig.8. (a) Current flow on gap-by-gap inductor; (b) path of induced eddy currents has butterfly-shaped loop.

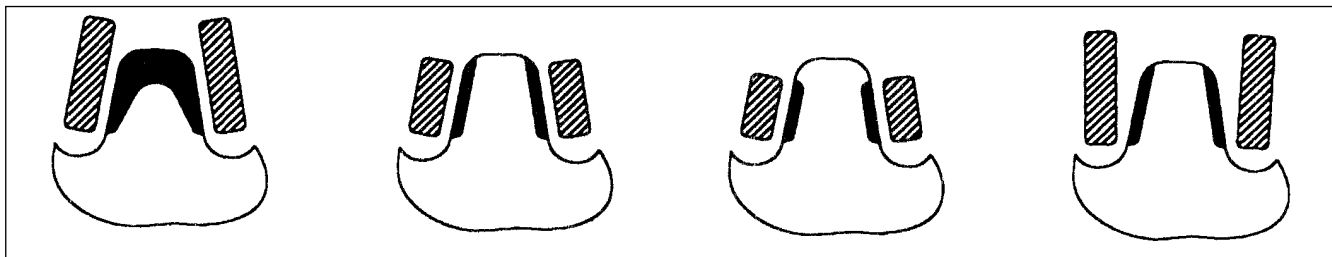


Fig.9. Effects of coil geometry on tooth-by-tooth hardness patterns.

Distortion

There can be appreciable shape/size distortion when applying tooth-by-tooth or gap-by-gap techniques for hardening large gears and pinions. Shape distortion is particularly noticeable in the last heating position. The last tooth can be pushed out 0.1 to 0.3mm. In some cases, distortion can be minimised by hardening every second tooth or tooth gap. Obviously, this will require two revolutions to harden the entire gear.

Final grinding is often required. As there is a linear relationship between the volume of required metal removal and grinding time, excessive distortion leads to a prolonged grinding operation and increases the cost. Heat treat distortion can also be compensated for during previous stages of gear design and manufacturing.

Even though there might be appreciable distortion when applying induction hardening to large gears and pinions (e.g., mill, marine and large transportation gears, etc.), this is not so significant when compared with distortion arising in thermochemical processing. Carburising operations require long-time soaking of gears (in some cases for up to 30 hours or longer) at temperatures of 850 to 950°C. At these temperatures, the large masses of steel expand to a much greater extent than that when only the gear surface layer is heated. The large-mass expansion during heating/soaking, and its contraction during cooling/quenching after carburising, results in much greater gear shape distortion than that after induction hardening.

In addition, large gears being held at temperatures of 850 to 950°C for many hours have little rigidity; therefore they can sag and have a tendency to follow the movement of their supporting structures during soaking and handling. During induction hardening, areas unaffected by heat, as well as areas with temperatures corresponding to the elastic

deformation range, serve as shape stabilisers and lead to lower more predictable distortion.

It is necessary to mention here that, due to small coil-workpiece air gaps (0.5 to 1.5mm) and harsh working conditions, the coils employed require intensive maintenance and have a relatively short life compared with inductors that encircle the gear.

End/edge effects

When designing this type of induction heating process, particular attention should be paid to electromagnetic end/edge effects and the ability to provide the required pattern in the gear face areas (gear ends) as well as along the tooth perimeter.

When a single-shot mode is used, an active coil length is approximately the same as the gear width. This mode is more limited in providing a uniform face-to-face hardness pattern than the scanning mode.

For the scanning mode, the coil length is typically, at most, half the gear thickness. In order to achieve the required face-to-face temperature uniformity, it is necessary to use a complex control algorithm, "Power and Scan Rate versus Coil Position." A short dwell at the initial and final stages of coil travel is often used. Thanks to preheating due to thermal conductivity, the dwell at the end of coil travel is usually shorter than that at the beginning.

When applying the scanning mode for hardening gears with wide teeth, two techniques can be used: one where the inductor is stationary and the gear is moveable, and another that assumes the gear is stationary and the inductor is moveable.

Fig.9 shows the effect of coil geometry on tooth-by-tooth hardness patterns¹³.

Tempering back

A concern when applying tooth-by-tooth or gap-by-gap hardening techniques is the problem of undesirable heating of the areas adjacent to the hardened area (tempering back). Concern about tempering back is particularly pronounced for *patterns A, D and I* when using gap-by-gap hardening and *patterns B and C* with tooth-by-tooth heat treating. Generally, there are two reasons why undesirable tempering can occur.

The external magnetic field coupling of the inductor can be the cause, when hardening tooth-by-tooth (*patterns B and C*), and can often be fixed relatively easily. The application of magnetic flux concentrators to the induction coil (Fig.10a) results in a drastic reduction of the external magnetic field. In cases with medium-sized tooth gaps, the allocation of concentrators can be difficult due to space limitations. The undesirable heating of the flanks of adjacent teeth can also be reduced by applying thin copper shields (copper caps); see Fig.10b. (The physics and application features of magnetic flux concentrators and shields are discussed elsewhere in the book).

Another cause typically arises when applying gap-by-gap hardening techniques (particularly for *patterns A, D and I*) and involves thermal conductivity effects. Heat is transferred by thermal conduction from a high-temperature

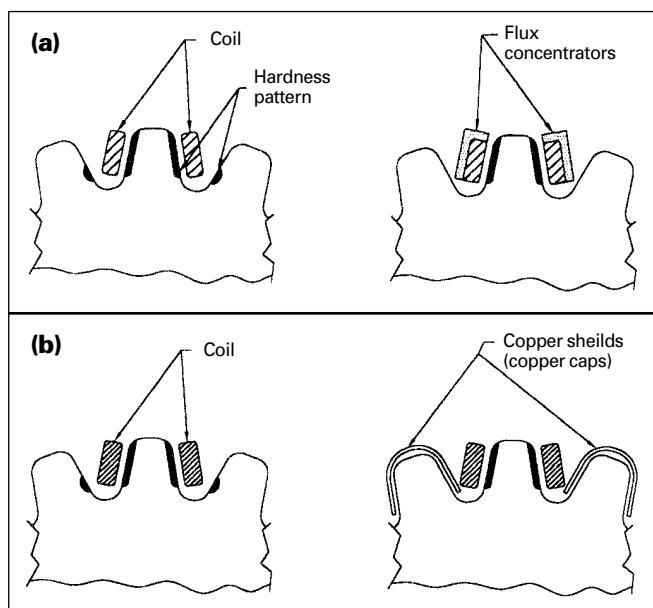


Fig.10. (a) Application of flux concentrators to inductor drastically reduces the external field. (b) Undesirable heating of adjacent teeth can be reduced by applying thin shields (copper caps).

region of the workpiece toward a lower-temperature region. According to Fourier's law, the rate of heat transfer is proportional to the temperature difference and the value of thermal conductivity. Most metals have relatively good thermal conductivity. During hardening, the surface temperature reaches a relatively high value and exceeds the critical temperature A_{C3} . Therefore, when heating one side of the tooth (i.e., patterns A, D and I), there is a danger that the opposite side of the gear tooth will be heated by thermal conductivity to an inappropriately high temperature, resulting in undesirable tempering back of previously-hardened areas.

Whether a hardened side of the tooth will be softened due to tempering back depends upon several factors, including the applied frequency, gear module, tooth shape, heat time, case depth and other pattern features. In the case of shallow and moderate case depths and large teeth, the root of the tooth, its fillet and the bottom of the tooth flank are typically not overheated due to thermal conductivity. The massive area below the tooth root serves as a heat sink, which helps to conduct excessive heat and protects the hardened side of the tooth from tempering back.

Conversely, the tooth tip and top of the tooth flank can be considered a troublesome area. Tempering back takes place because there is a relatively small mass of metal at the tooth tip. In addition, heat has a short distance to travel from one (heating) side to the other (already hardened) side of the tooth (Figs. 11a and b).

In order to overcome the problem of tempering back, additional cooling blocks can be used. Extra cooling protects already-hardened areas while heating unhardened areas of the gear (Fig. 11c). Even though external cooling is applied, depending on the tooth shape and process parameters, there may still be some unavoidable tempering back. This is typically insignificant and acceptable.

Tooth-by-tooth and gap-by-gap techniques can harden gears submerged in a temperature-controlled tank of quenchant. This approach was applied in the original Delapena induction hardening process. In this case, quenching is practically instantaneous and both controllability and repeatability of the hardness pattern is improved, although additional power is required. The fact that a gear is submerged in quenchant also helps to prevent the tempering back problem, as well as crack development in the tooth root. In addition, the quenchant serves as a coolant to the inductor. Therefore, in submerged hardening, an induction coil does not have to be water-cooled.

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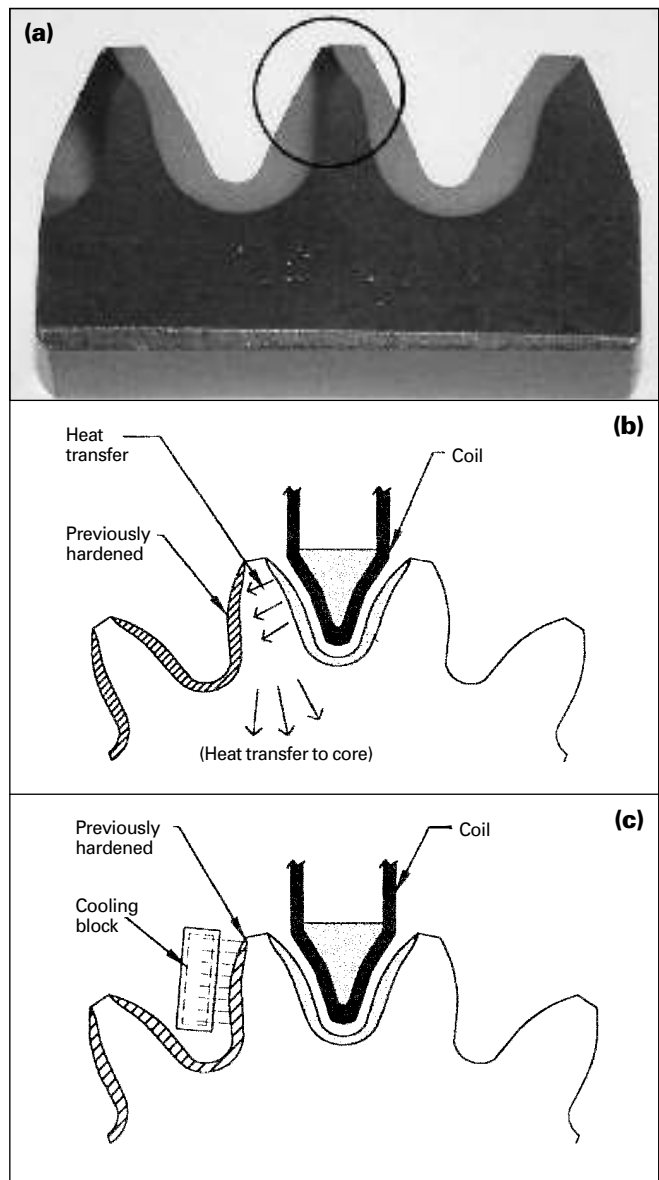


Fig.11. (a) Tip of tooth flank can be a trouble area with regard to the tempering back of the adjacent tooth (b), because of the relatively small mass of metal there. Cooling blocks are added (c) in order to overcome tempering back of the previously-hardened tooth.

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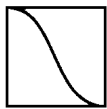
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In the next edition of HEAT TREATMENT OF METALS, the second and concluding part of this article focuses on gear spin hardening (encircling inductors).

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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

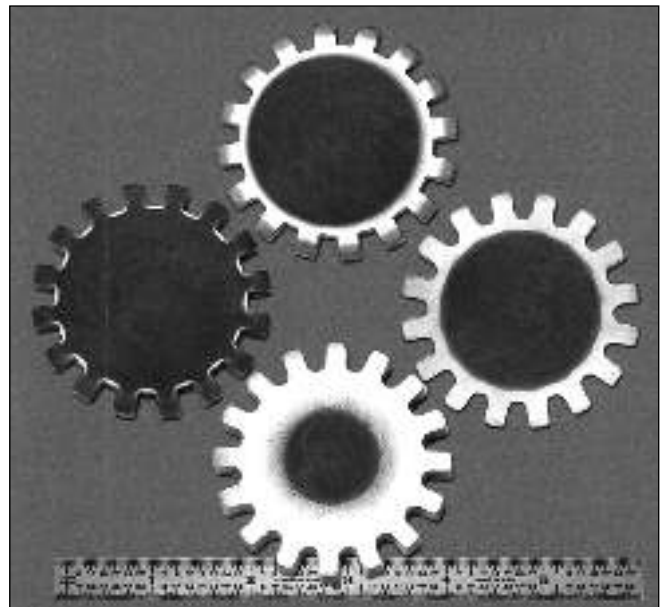


Fig.12. Diversity of induction hardening patterns, with variations in time, frequency and power. (Courtesy of J. LaMonte, Inductoheat Inc.).

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

*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.

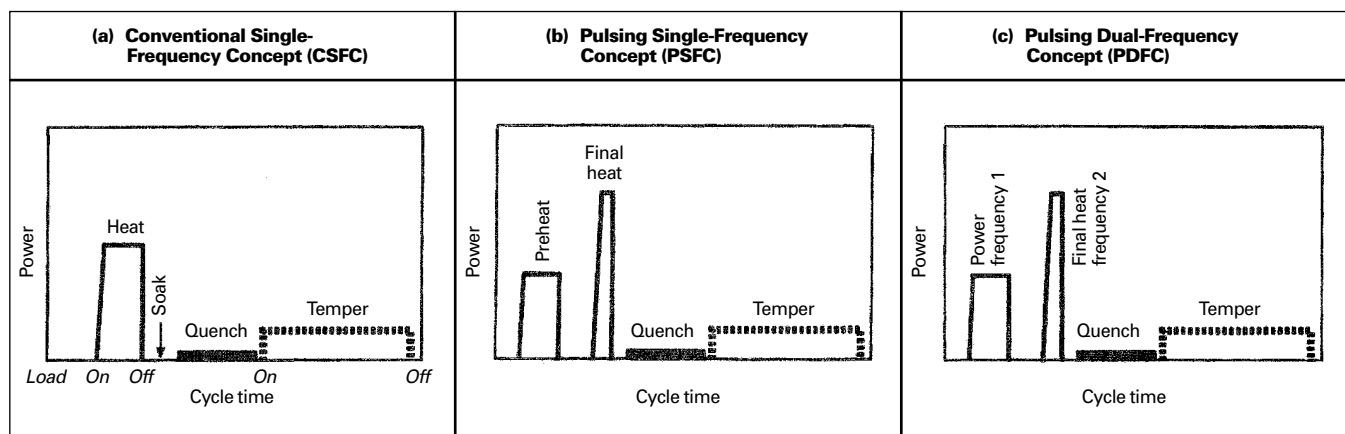


Fig.13. Concepts of gear hardening by induction.

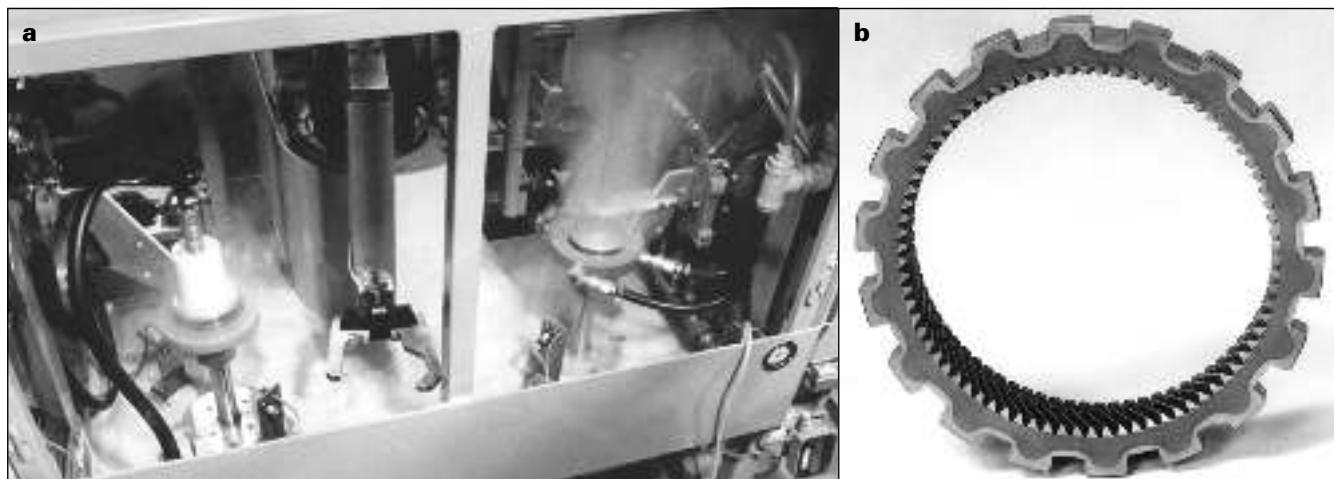


Fig. 14. (a) Equipment used to harden OD and ID of gears such as that in (b). (Courtesy of Inductoheat Inc.).

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.

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



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

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 micro-structure, 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

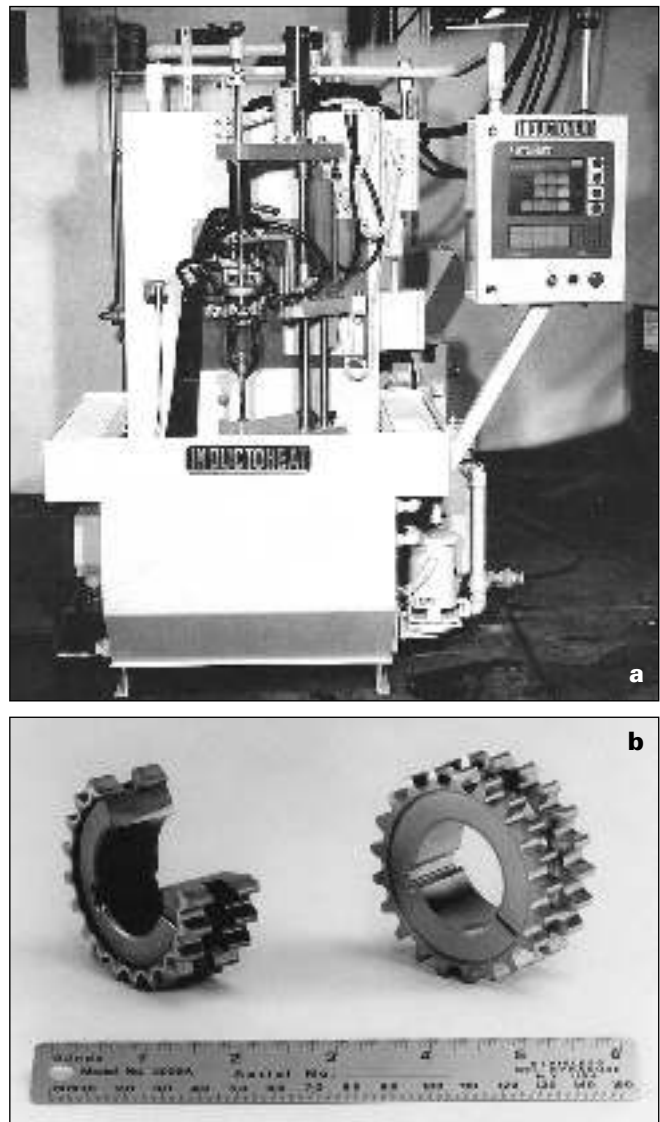


Fig.16. A unitised induction system (a), capable of providing both CSFC and PSFC gear hardening, is used to harden the double sprocket shown in (b).

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

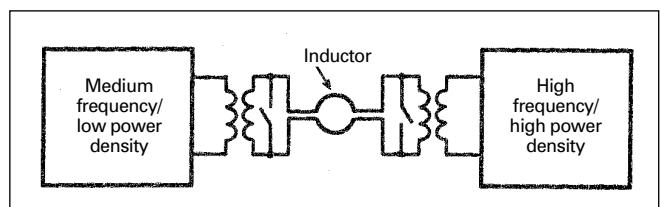


Fig.17. Using one coil and two inverters for PDFC gear hardening.

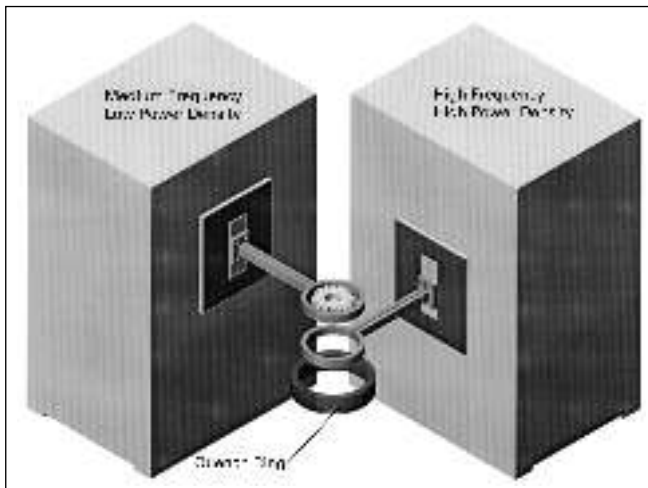


Fig.18. One coil is used for preheat and a second is for final heat in the common approach to PDFC hardening.

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.

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

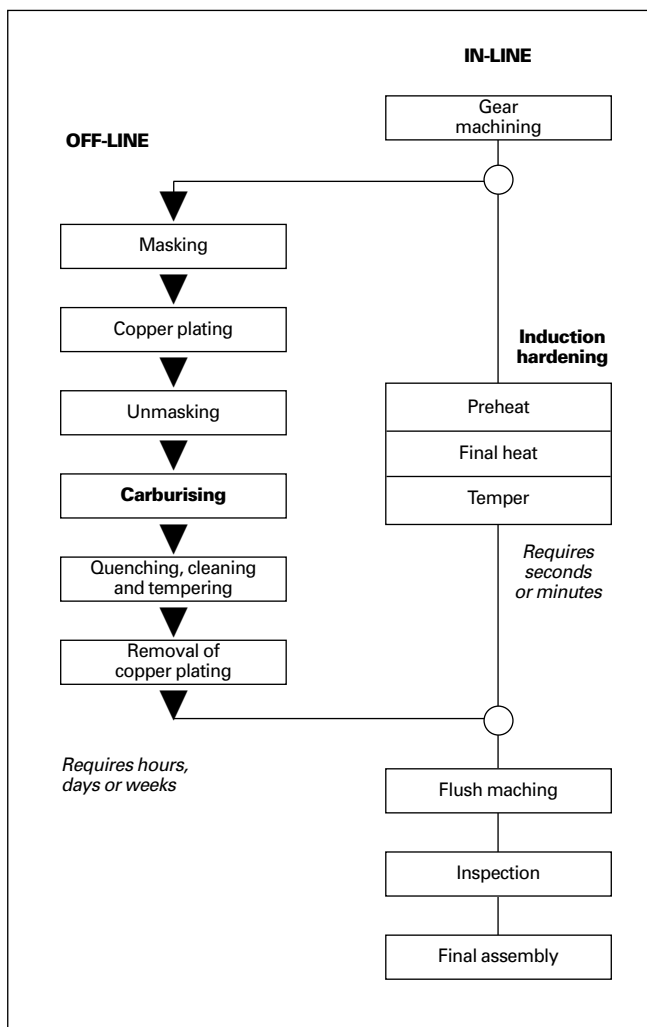


Fig.20. Steps required for carburising compared with those for induction hardening¹⁸.

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 techniques²⁰. These new low-alloyed carbon steels, invented by Dr. K. Shepelyakovskii²⁰ and distributed by ERS Engineering²¹, 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}.

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

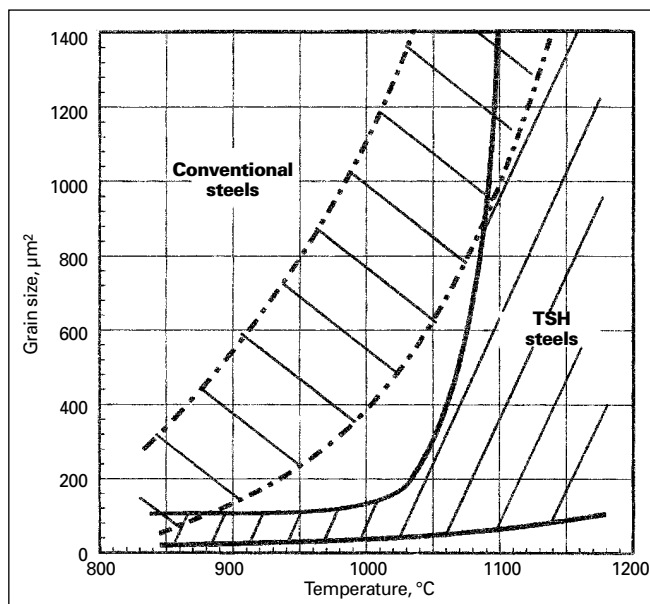


Fig.22. Grain growth for TSH steels versus that of conventional grades²⁰.

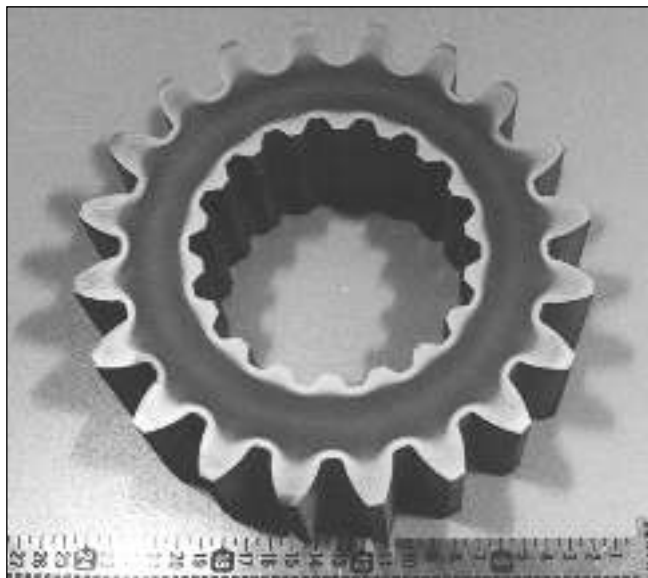


Fig.23. Induction heat-treated gear made from TSH steel.