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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 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,

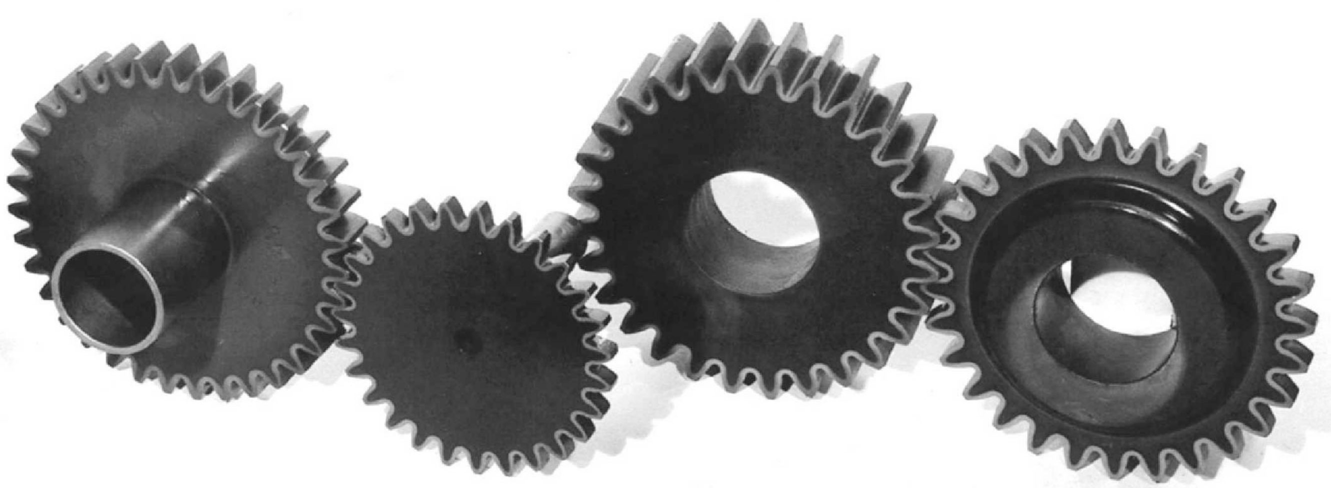

Fig.1. Typical induction-hardened gears.

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 composition[1-5].

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 austenisation 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 austenisation. 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.

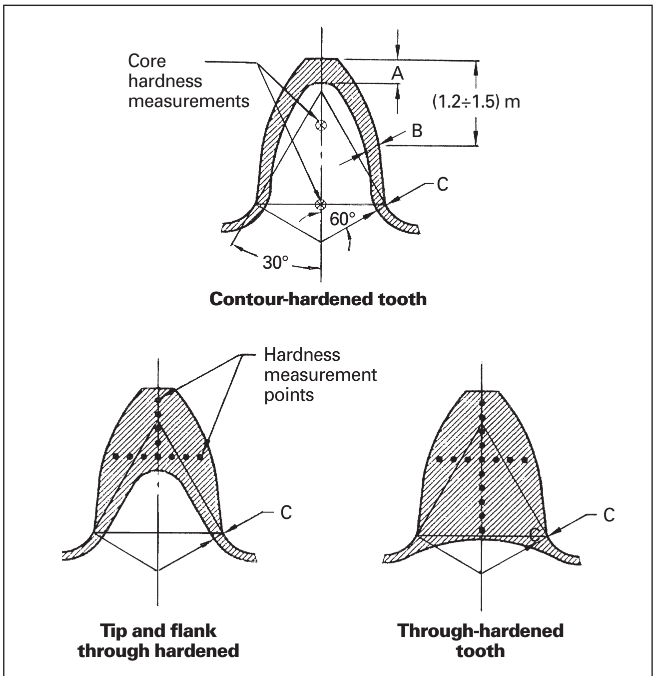

Fig.2. Typical locations of gear profile measurements. Depending on type of gear and its application, specific procedures are created for these measurements.

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. Conversly, 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.

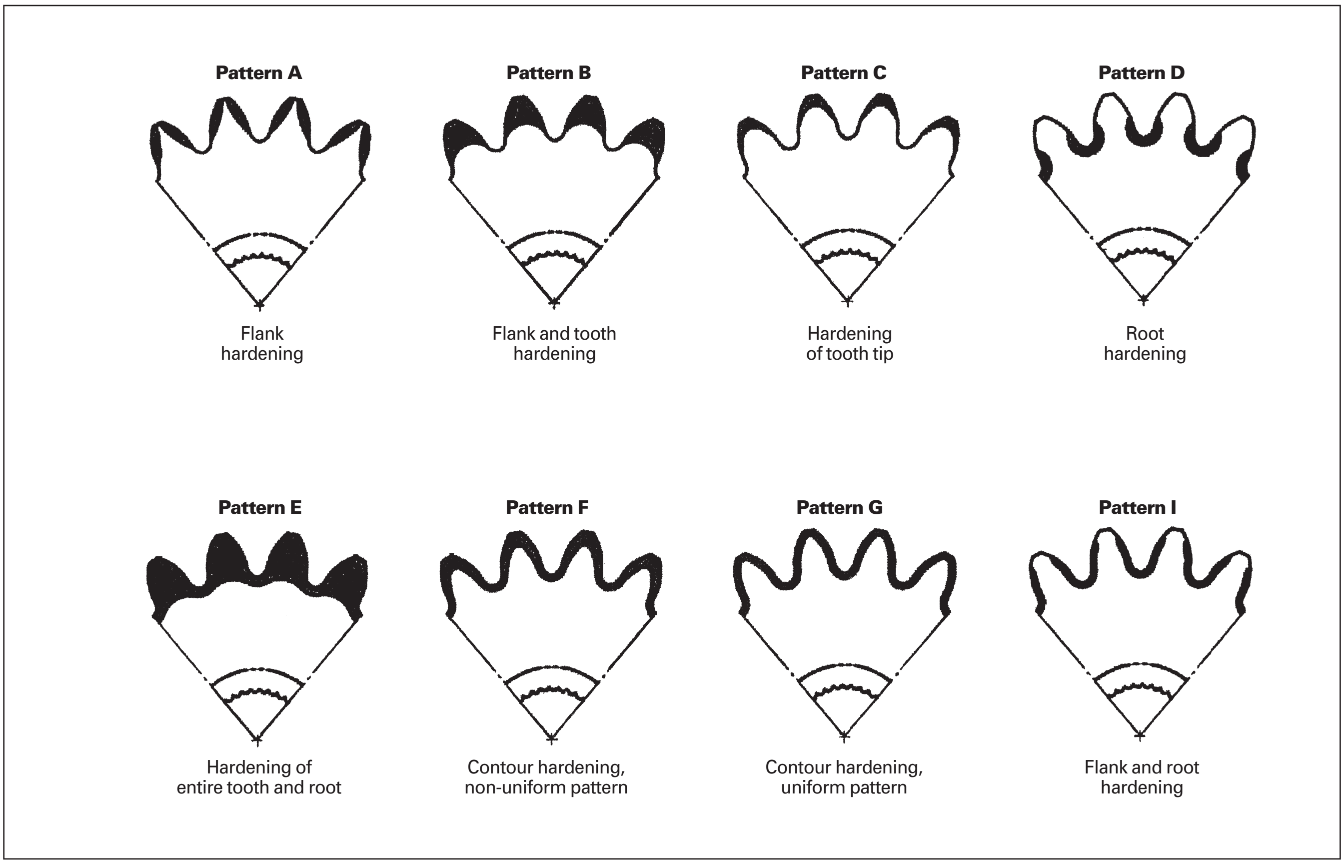

Fig.3. Induction hardening patterns of gears.

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

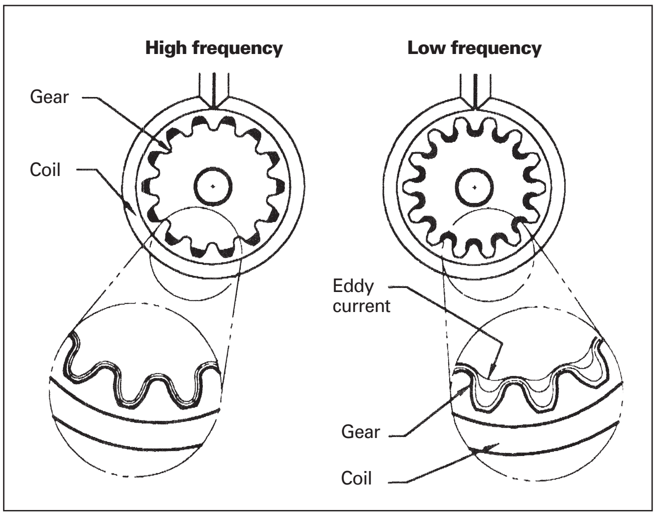

Fig.4. Frequency influence on hardness profile with encircling induction coil: (a) high frequency; (b) low frequency.

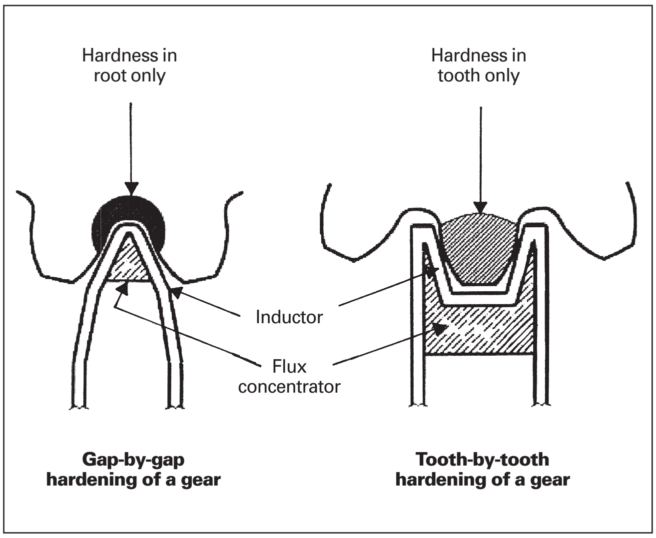

Fig.5. Gap-by-gap and tooth-by-tooth induction hardening.

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 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 a frequencies of 70kHz and even higher have been used. For example, the NATCO submerged technique[12] 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.

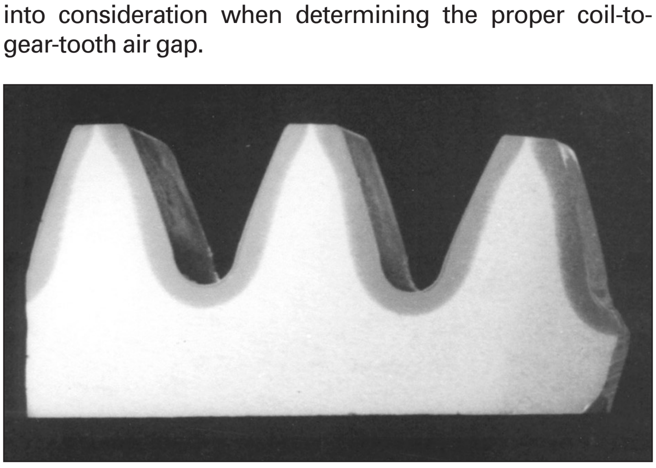

Fig.7. Gap-by-gap pattern profile. (Courtesy of Inductoheat Inc.).

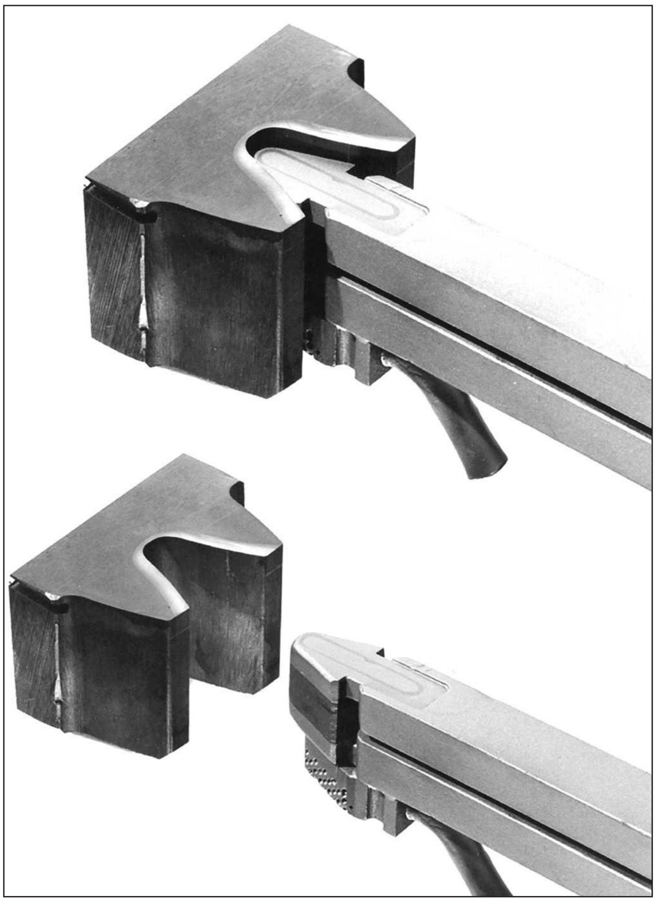

Fig.6. Gap-by-gap inductor and gear. (Courtesy of Inductoheat Inc.).

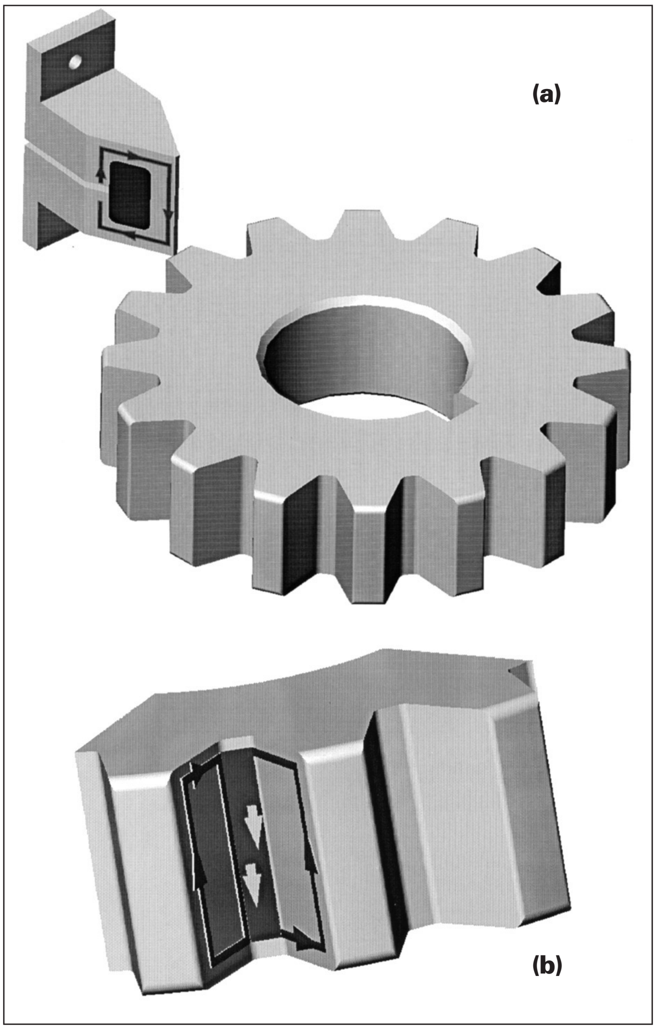

Fig.8. (a) Current flow on gap-by-gap inductor; (b) path of induced eddy currents has butterfly-shaped loop.

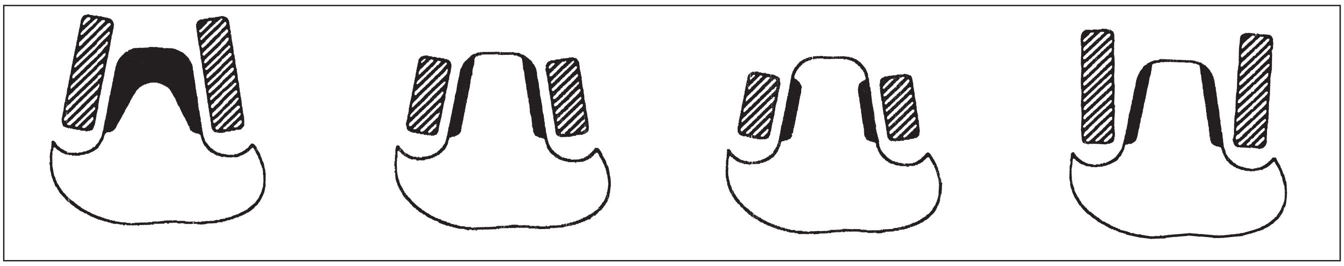

Fig.9. Effects of coil geometry on tooth-by-tooth hardness patterns.

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.

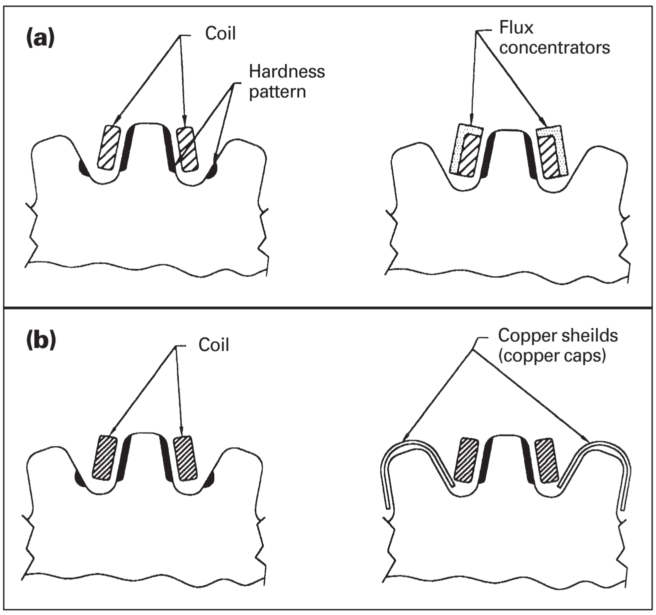

Fig.10. (a) Application of flux concentrators to inductor drastically reduces the external field. (b) Undesirable heating of adjacent teeth can be reduced by applying thin shields (copper caps).

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 patterns[13].

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 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.

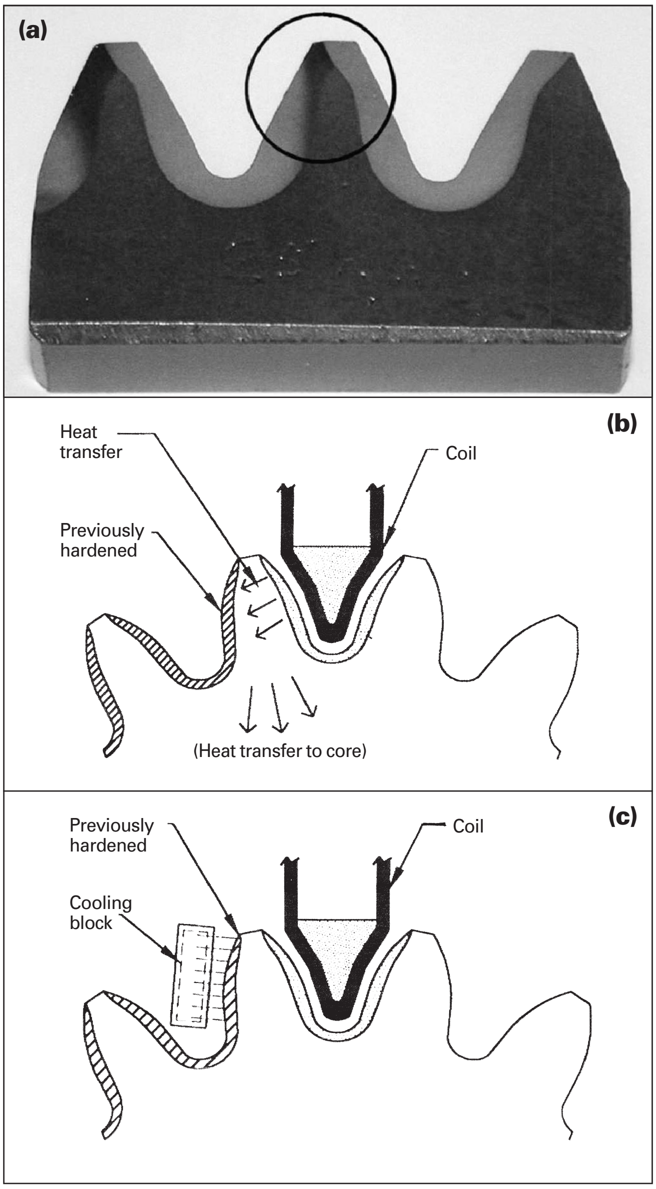

Fig.11. (a) Tip of tooth flank can be a trouble area with regard to the tempering back of the adjacent tooth (b), because of the relatively small mass of metal there. Cooling blocks are added (c) in order to overcome tempering back of the previously-hardened tooth.

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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.

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