Gear Heat Treating by Induction

Dr. Valery Rudnev, Don Loveless, Brian Marshall,
Dr. Konstantin Shepeljakovskii, Norm Dyer and Micah Black

The induction hardening and tempering of gears and critical components is traditionally a hot subject in heat treating. In recent years, gear manufacturers have increased their knowledge in this technology for quality gears.

In contrast to carburizing and nitriding, induction hardening does not require you to heat a whole gear. With induction, the heating is localized to those areas where metallurgical changes are desired. The induction hardening process is a combination of electromagnetic, heat transfer and metallurgical phenomena that occurs when a workpiece (i.e. gear) is heated rapidly to a temperature above that which is required for a phase transformation to austenite and then rapidly quenched. One of the goals of induction hardening is to provide a fine grain 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. Another goal deals with an ability to provide significant compressive stresses at the workpiece surface. This is a crucial feature, since it reduces crack propagation.

Induction heat treating is typically accomplished in a relatively short time and with high efficiency because energy is applied to the part only where it is needed. Induction equipment can be easily automated and incorporated into a work cell. The ability to heat treat in-line, as opposed to batch processing, provides high productivity and controllability and takes less shop floor space.

Fig. 1—Sample induction hardened gears.

The kind of steel or iron used and its prior microstructure and gear performance characteristics dictate the required hardness profile, gear strength and residual stress distribution. Minimum gear shape distortion and pattern repeatability are among the most critical parameters that should be satisfied when heat treating gears.

Not all workpieces are well suited for induction heating. The best candidates are parts that have a classical geometry, including bushings, bars, pins, rings, plates, shafts, etc. External spur and helical gears, bevel and worm gears, internal gears, racks and sprockets are also among the parts that often undergo heat treating by induction (Fig. 1).

Hardening Patterns

The first step in designing an induction gear heat treatment machine is specifying the required hardness profile. There is a common misconception that a uniform contour profile is always the best pattern for gear hardening applications. It is not. In many cases, a certain hardness gradient profile can provide a gear with better performance. Let's briefly evaluate a variety of hardening patterns (Fig. 2) and their effect on a gear's load carrying capacity and life.

Pattern A is a flank hardening pattern that has been used since the late 1940s for hardening large gears (outside diameter greater than 300 mm with tooth modules of 10–12 and larger). This pattern provides the required wear resistance, but the typical failure mode of gears with this type of pattern is a fatigue crack initiating at the tooth root area. It is typically strongly recommended that one use a pattern that hardens the root area as well, such as that pictured in pattern I.

Pattern B is a flank and tooth hardening pattern. This pattern has a similar shortcoming to the previous one, featuring poor load carrying capacity. It can be used in cases where wear resistance is of prime concern. However, patterns E, F and G provide better results

Dr. Valery Rudnev

is group director, science & technology, for Inductoheat, Inc. He has an M.S. in electrical engineering and a Ph.D. in induction heating. From 1993 to 1999, he worked as chief scientist for Inductoheat. He has 24 years of experience in induction heating. His credits include 14 patents and 92 scientific and engineering publications.

Don Loveless

is group vice president, research & development, for Inductoheat, Inc. He has 28 years of experience in induction heating. He concentrates on the research and development of high-/medium-frequency thyristorized and transistorized power supplies. Among his credits are 4 patents and 18 research/engineering publications devoted to different aspects of induction heating.

Brian Marshall,

applications engineer, joined Inductoheat, Inc. in 1979. He has been involved in the design and development of machines and processes for a variety of induction heat treating applications, including heat treatment of gears.

Dr. Konstantin Shepeljakovskii,

retired, has a Ph.D. in material science. Among his credits are more than 60 patents. He works as a consultant for Inductoheat, Inc. and NPO TechMash (Russia).

Norm Dyer,

international sales manager, joined Inductoheat, Inc. in 1989. He holds a B.Sc. degree from Wayne State University. Mr. Dyer has been involved in the improvement of a variety of induction metal heat treating processes.

Micah Black,

induction coil design supervisor, joined Inductoheat, Inc. in 1981. He has been involved in the development of a number of advanced induction processes and coil designs. Among his credits are 6 engineering/research publications.

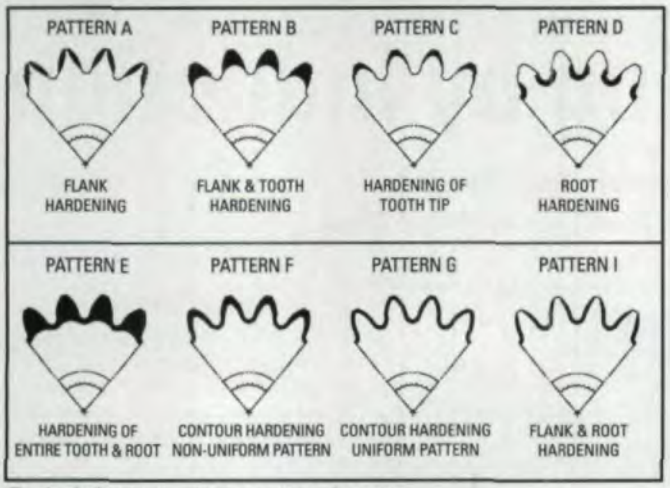

Fig. 2—Induction hardening patterns for gears.

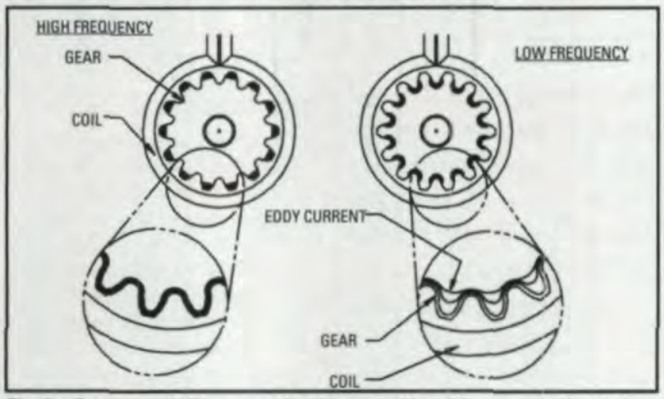

Fig. 3—Frequency influence on hardness profile with an encircling induction coil.

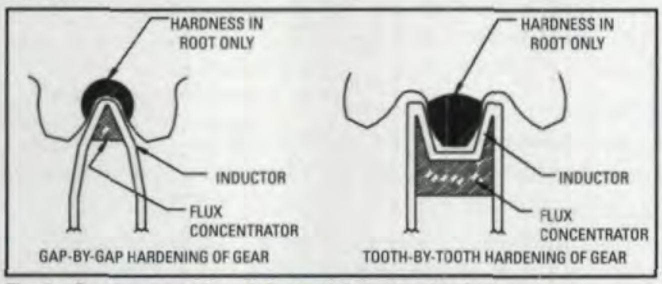

Fig. 4—Gap-by-gap and tooth-by-tooth induction hardening.

Fig. 5—Effects of changes in time, frequency and power on the hardening patterns in a steel shaft.

when wear, tear and fatigue resistance are required.

Pattern C is a tooth tip hardening pattern. In this case, the gear has minimum shape distortion. The application of gears with this pattern is extremely limited because the two most important gear areas (flank and root) are not hardened. In most cases, patterns F and G would be better choices.

Pattern D is a root hardening pattern. Application of this pattern is very limited as well, since it has poor wear resistance. Theoretically, it is possible to imagine the necessity of using this pattern as well as the previous one; however, practically, it is better to use another pattern, such as pattern I.

Pattern E is one of the most popular induction hardening patterns, particularly for small gears and sprockets. Since the body of the tooth is through hardened, there is a danger of brittle fracture in gears subjected to shock loads. Therefore, one typically applies a low-temperature tempering that lowers the final hardness down to 52–58 HRC. This pattern offers good resistance to wear and pitting.

Patterns F & G are popular patterns for medium size gears in many applications. Case depth at the root area is typically 30–40% of the depth in the tooth tip. It is very important to harden an entire gear perimeter, including flank and root area. A relatively ductile tooth core (28–44 HRC) and a hard surface (56–62 HRC) provide a good combination of such important gear properties as wear strength, toughness and bending fatigue.

Pattern I is one of the most popular choices for induction hardening large gears and pinions (300 mm or more in outside diameter) with coarse teeth (modules greater than 10–12). This pattern provides an exceptional combination of fatigue and tear strength and shock resistance, which is very important for heavily loaded gears and pinions experiencing severe shock loads.

Coil Geometry and Heat Mode

The variety of required hardness profiles calls for different coil designs and heat modes. Development, including coil design, is largely based on induction principles, the results of mathematical evaluation and experience with previous jobs. The development establishes not only process parameters, including cycle times and power levels, but also coil geometry.

Tooth-by-tooth and gap-by-gap inductors. Generally speaking, gears are induction heat treated by either encircling the part with a coil (Fig. 3) or, in larger gears and pinions, heating them tooth-by-tooth or gap-by-gap (Fig. 4). Both tooth-by-tooth and gap-by-gap techniques can be realized by applying a single-shot or scanning mode. A gap-by-gap inductor can be designed to heat only the root and/or flank of the tooth, leaving the tip and the core soft and ductile. There are many variations of coil designs applying these principles. Probably one of the most popular is a "zigzag" shaped inductor.

Generally speaking, power requirements of both tooth-by-tooth or gap-by-gap hardening are relatively low, and applied frequencies are usually in the range of 1-10 kHz. At the same time, this is a time-consuming process with a low production rate. Pattern uniformity is very sensitive to coil positioning. In addition, there is typically an appreciable shape or size distortion. Shape distortion is particularly noticeable in the last heating position. The last tooth can be pushed out by 0.1-0.3 mm. Therefore, final grinding is often required. Distortion can be minimized by hardening every 2nd tooth or tooth gap, (but this requires 2 revolutions to harden the entire gear). It is necessary to mention here that due to small coil-workpiece air gaps (0.5-1.5 mm) and harsh working conditions, the induction coils often require intensive maintenance and have relatively short lives compared with inductors that encircle the gear. When designing this type of inductor, particular attention should be paid to electromagnetic end/edge effects and the ability to provide the required pattern in the gear face areas.

Encircle inductors. When applying encircle coils, there are five parameters that play a dominant role in obtaining the required hardening pattern: frequency, power, cycle time, coil geometry and quenching conditions. Proper control of these parameters can result in totally different hardened profiles. Figure 5 illustrates a diversity of induction hardening patterns that were obtained on the same carbon steel shaft thanks to 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. 3, left picture). When hardening the tooth root, a lower frequency and lower power density should be used (Fig. 3, right picture). A high power density generally gives a shallow pattern; conversely, a low power density will produce a deep pattern.

Figure 6 shows three of the most popular design concepts of the induction gear heat treating processes that employ encircle-type coils: conventional single frequency concept (CSFC), pulsing single frequency concept (PSFC) and pulsing dual frequency concept (PDFC). All three concepts can be used in either a single-shot or scanning mode.

The conventional single frequency concept is typically used for hardening gears with small teeth. As one can see in Figure 2 (patterns B & E), the teeth are usually through hardened. Quite often, CSFC can also be successfully used for medium size gears. As an example, Figure 7 shows the induction gear hardening machine that applies this concept. The part being heat treated in this application is an automotive transmission component with helical teeth on the inside diameter and large teeth on the outside diameter. Both the inside diameter and the outside diameter require hardening (Fig. 8). The hardening of the inside diameter gear teeth requires a higher frequency than the outside diameter. Therefore, a frequency of 10 kHz was chosen for O.D. hardening, and a 200 kHz frequency was chosen for I.D. heating. Precise control of the hardening operations and a sophisticated design concept minimize part distortion and provide desirable residual stresses in the finished gear.

Gears are conveyed to the machine, where they are transferred by a cam-operated robot to the spindle of a heat treating

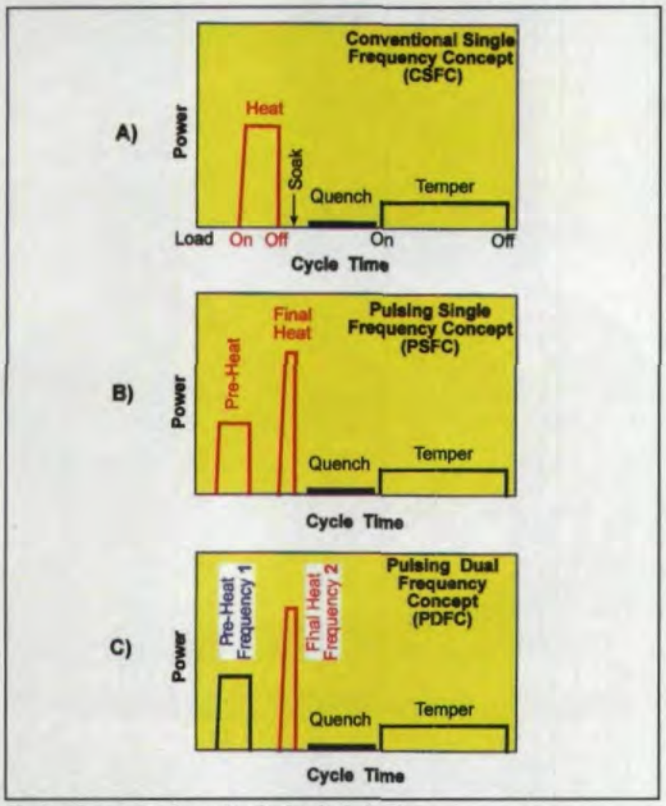

Fig. 6—Concepts of gear hardening by induction.

Fig. 7—Induction heat treating an automotive transmission gear with internal and external teeth.

Fig. 8—Cross section of an automotive transmission component after induction hardening.

station. Parts are monitored at each station and accepted or rejected based on all the major factors that affect gear quality. This includes energy input into the part; quench flow rate; temperature and 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.

Quite often, in order to prevent problems such as pitting, spalling, tooth fatigue and endurance, it is necessary to harden a contour of the gear (contour hardening). 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 a required contour hardness profile.

The first factor is that with encircle-type coils, the root area does not have a good coupling with the inductor compared to the coupling at the gear tip. Therefore, it is more difficult to induce energy in the gear root. Secondly, there is a significant heat sink located under the gear root (below the base circle, Fig. 3). In order to overcome these difficulties and be able to meet customer specifications, the pulsing single frequency concept (PSFC) has been developed (Fig. 6b). In many cases, PSFC allows the user to avoid the shortcomings of CSFC and obtain a contour hardening profile. Pulsing provides desirable heat flow towards the root of the gear tooth without noticeable overheating of the tooth tip.

A typical "dual pulse" contour hardening system, which applies a pulsing single frequency concept, has been discussed in Reference 2. This machine is designed to provide gear contour heat treatment (including pre-heating, final heating, quenching and tempering) with the same coil using one high frequency power supply. Figure 6b 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. Obviously, preheating reduces the amount of energy required in the final heat.

A third concept—the pulsing dual frequency concept (PDFC)—is not a new one. The idea of using two different frequencies has been around since the late 1950s. This concept was primarily developed to obtain the contour hardening profile of helical and straight spur gears. Since several different companies, including Contour Hardening, Inductoheat and others, have pursued this idea, several different names and abbreviations have been used to describe it. However, regardless of the differences in nomenclature and the slight process variations, the basic idea is the same.

According to PDFC (Fig. 6c), the gear is preheated within an induction coil to a temperature determined by the process features that is usually 50–100°C below the critical temperature A_{c1}. Typically, this is accomplished by using a medium frequency (3–10 kHz).

Depending on the type of gear, its size and material, a high frequency (30–450 kHz) and high power density are applied during the final heat stage. For the final heating stage, the frequency selected allows the current to penetrate only to an exact repeatable depth. Quenching is done to complete hardening and bring the gear to ambient temperature. In some cases, dual frequency machines produce parts with lower distortion and more favorable distribution of residual stresses compared to other techniques.

The main drawback of this process is its complexity and high cost, since it is necessary to have 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 quite low.

Special attention should be paid when designing induction hardening machines for powdered steel gears. These gears are affected to a much larger extent by variations in the material properties of powder metals as compared to gears made by casting or forming. This is because the electrical resistivity, thermal conductivity and magnetic permeability strongly depend on the density of the powder metal.

TSH Technology for Gears

An impressive result can be achieved not only by developing a sophisticated process, but also by using existing processes with a combination of advanced steels. Through and surface hardening technology (TSH) is a synergistic combination of advanced steels and special induction hardening techniques. These steels were invented by Dr. K. Shepeljakovskii (Ref. 6). The new low-alloyed carbon steels are characterized 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, carburizing or quenching and tempering.

Main features of TSH technology include:

- TSH steels are relatively inexpensive, incorporating significantly smaller amounts (3–8 times less) of alloying elements such as manganese, molybdenum, chromium and/or nickel.
- Lower induction hardening frequency (1–10 kHz) reduces power supply cost.
- High surface compressive residual stresses (500 Mpa/73 ksi +).
- Hardened depth is primarily controlled by the steel's chemical composition and initial microstructure. This makes the heat treating process repeatable and robust.
- Reduced chance of overheating part edges and sharp corners due to end effect.

Figure 9 shows an induction heat treated gear made from TSH steel. One of the unique features of that gear is that instead of using a two-step approach (first O.D. heat and then I.D. heat, or vice-versa), that gear has been heated and quenched in a single step using only one inductor. O.D. and I.D. teeth have fine grained martensite with a hardness of 62 HRC. The microstructure of the core is a combination of very fine pearlite and bainite having a hardness of 25–40 HRC.

TSH technology parts are stronger and more durable than some made of conventionally heat treated standard steels. Typical applications include gears, bushings, shafts, coil springs and bearings (Ref. 6).

Induction Tempering

The stress relieving/tempering process takes place after the part is hardened. It is a subsequent but no less important step in metal heat treating. The main purpose of tempering is to decrease the gear brittleness without causing too great a decrease in the as-quenched hardness, to relieve internal stresses, and in some cases to improve shape stability (Ref. 5).

A conventional method of tempering induction hardened gears is to heat them in an oven or a gas-fired or infrared furnace, which is typically located in another area of the plant. This has penalties in terms of floor space, labor and time needed to transport parts. In addition, a furnace tempering operation may take two to three hours to complete. Short-time induction tempering was developed to overcome these drawbacks.

Time and temperature are two of the most critical parameters in short-time induction tempering. However, temperatures higher than those used for furnace tempering must be used to provide a similar effect. There are several ways to determine the time-temperature correlation between conventional long-time, lower temperature furnace tempering and short-time, higher temperature induction tempering, including, for example, the Hollomon-Jaffe equation and the Grange-Baughman tempering correlation.

There is a common misconception that tempering removes all internal stresses. Tempering does decrease some stresses. It makes the steel softer and reduces the chance of noticeable distortion and the possibility of cracking. As a matter of fact, it is not really desirable to relieve all stresses. As mentioned above, in most gear heat treating applications, the existence of good compressive residual stresses at the gear surface is useful and very desirable since it reduces the possibility of crack development.

There is a balance of residual stresses in the workpiece. Therefore, if in certain areas of the gear there are compressive residual stresses, then somewhere within the workpiece, there must be tensile stresses. Applied stresses are maximum at the gear surface and then rapidly drop off. Therefore, one of the important "duties" of tempering is not only the reduction of tensile stresses, but also the shifting of the maximum of these stresses toward the core.

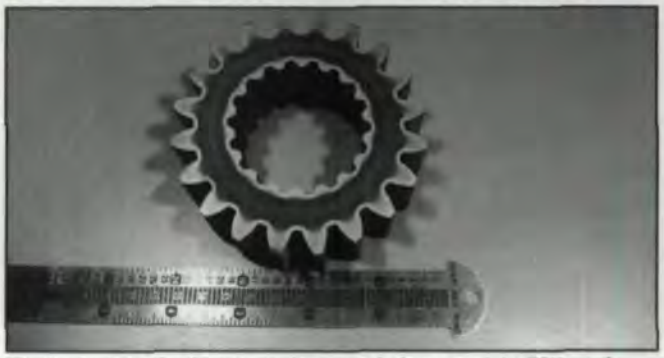

Fig. 9—An induction heat treated gear made from specialty TSH steel.

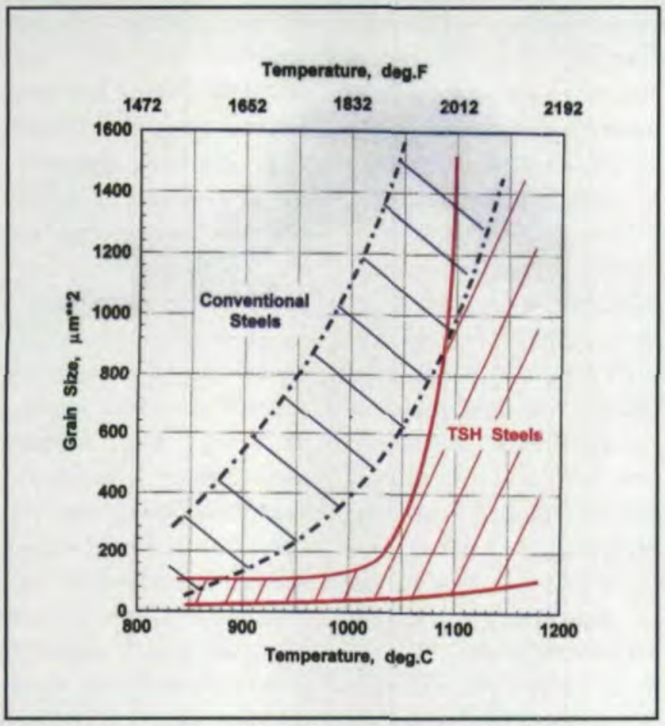

Fig. 10—Grain growth for TSH steels vs. that of conventional grades.

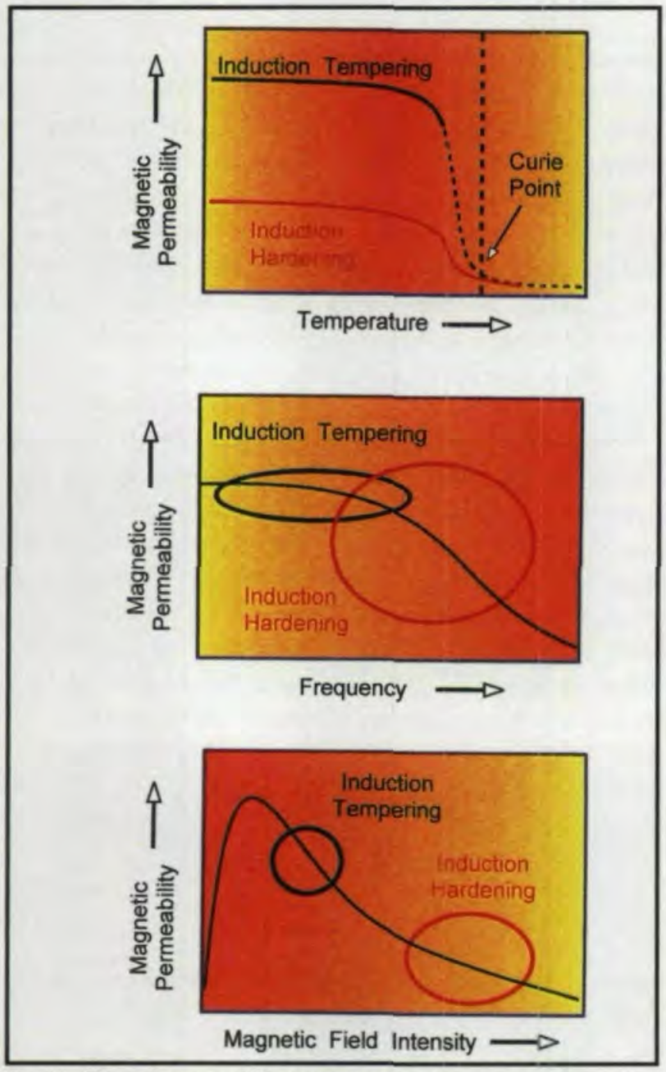

Fig. 11—Magnetic permeability vs. temperature, frequency and magnetic field intensity.

It is important that the time from quench to temper be held to a minimum. If this "transient time" is long enough, the internal stresses may cause a noticeable size and shape distortion, or even cracking. Therefore, a long transient time between quenching and tempering will *decrease or eliminate the tempering benefits*.

In the case of induction tempering any complex parts (including gears), the choice of frequency, power density and coil geometry is dictated by the need to apply enough energy into certain areas of the part. In gear tempering applications, it is necessary to induce enough energy into the root area of the tooth without overheating its tip.

The root of the gear is a critical area because the maximum concentration of stresses is typically located there. As a result, fatigue cracks occur primarily in the root area. Therefore, it is very important for this area to be stress relieved. There are three factors that make this task quite a complicated one. Two factors are similar to hardening and were discussed above. One of them deals with poor electromagnetic coupling between the coil and the tooth root compared with the tooth tip. Another one deals with the existence of a heat sink phenomenon in the root. The third factor derives from the fact that the tempering temperatures are always below the Curie point. Therefore, the gear is magnetic and the skin effect is always pronounced (Fig. 3, left figure). The use of high frequency for induction tempering will result in an essential power surplus in the tip of the tooth compared to its root and will have a tendency to overheat edges and sharp corners. In order to overcome these difficulties, low frequency, loose coil coupling and low power density should be used for tempering.

As discussed above, it is possible to harden and temper gears in the same coil using *the same power supply*. In some cases, it is the best concept and has an obvious low capital cost advantage and less tooling to store. In other cases, it might not best suit customer requirements.

Since the power density required for tempering is quite low, it is necessary to heat a gear at a slow rate to avoid tooth tip overheating. Depending upon the type of power supply, this is not always an easy task from the load matching point of view. In addition, the depth of current penetration in carbon steel at tempering temperatures is very small compared to its value during hardening. This is due to the fact that tempering temperatures are always below the Curie point, and therefore, steels are always in a magnetic state. In addition, the relative magnetic permeability of steel during induction tempering is more than ten times higher compared to the permeability of steel during induction hardening. This is due to the low magnetic field intensities used in induction tempering (Fig. 11).

A substantial increase in magnetic permeability results in a significant decrease in penetration depth of an induced current. Therefore, in order to heat a gear for tempering to the same depth as hardening, it is wise to use a lower frequency.

In addition, time required for induction tempering is typically 2–4 times that of induction hardening. Therefore, when one uses the same coil for hardening and tempering, the production and power supply utilization might suffer.

Heating for tempering with a separate coil and dedicated power supply is a more costly solution from a capital investment point of view, but at the same time, it has several noticeable advantages. The current distribution and power density can be optimized specifically for the tempering operation. A separate, loosely coupled, channel-type, single- or multi-turn coil can be used effectively for this purpose. Equipment will be used very effectively with high production. One hardening machine can operate in conjunction with two or three tempering machines.

The decision to induction temper should be carefully weighed (Ref. 5). Some metallurgists are not comfortable with tempering for a short time and then only in the hardened area. They feel that furnace heating of the entire part and holding it a temperature for hours, vs. seconds or minutes, is more reliable. The key to any gear or critical component production process is how well the finished part performs in service. An induction tempered gear, like any other machine component, should be thoroughly tested and evaluated for reliability. Necessary test data for induction and furnace tempered parts should be compared. It is important to remember that the surface temperature alone is not a valid indication of a proper temper. If tempering has been done correctly, there will be only a slight reduction in hardness, which will be more than offset by the benefits obtained, including internal stress relief, improved ductility or toughness, and shifting of the maximum tensile stress farther away from the applied stress.

The advantages of induction tempering—system compactness, single part processing, energy efficiency, and precise control and monitoring of an individual part—in many cases far outweighs the disadvantages and fear of the untried.

Conclusion

Space limits this discussion to major features of induction gear heat treating. There are many aspects involved in designing and manufacturing contemporary gear hardening and tempering systems. This includes an effect of prior microstructure and grain size on hardening pattern. Others deal with quenching, cracking, shape/size distortion and residual stress distribution. ○

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