Induction Hardening of Gears and Critical Components

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Management Summary

Induction hardening is a heat treating technique that can be used to selectively harden portions of a gear, such as the flanks, roots and tips of teeth, providing improved hardness, wear resistance, and contact fatigue strength without affecting the metallurgy of the core and other parts of the component that don't require change. This article provides an overview of the process and special considerations for heat treating gears. Part I covers gear materials, desired microsctructure, coil design and tooth-by-tooth induction hardening. Part II, which will appear in the next issue, covers spin hardening and various heating concepts used with it.

Introduction

Over the years, gear manufacturers have gained knowledge about how technology can be used to produce quality parts. The application of this knowledge has resulted in quieter, lighter and lower cost gears that have an increased load-carrying capacity to handle higher speeds and torques while generating a minimum amount of heat and noise.

Gear performance characteristics (including load condition and operating environment) dictate the required surface hardness, core hardness, hardness profile, residual stress distribution, grade of steel and the prior microstructure of the steel.

In contrast to carburizing and nitriding, induction hardening does not require heating the whole gear. With induction, heating can be localized to only those areas in which metallurgical changes are required. For example, the flanks, roots and tips of gear teeth can be selectively hardened.

A major goal of induction gear hardening is to provide a fine-grain martensitic layer on specific areas of the part. The remainder of the part is unaffected by the induction process. Hardness, wear resistance, contact fatigue and impact strength increase.

Another goal of induction gear hardening is to produce significant compressive residual stresses at the surface and in a subsurface region (Refs. 1–4). Compressive stresses help inhibit crack development and resist tensile bending fatigue.

Not all gears and pinions are well suited for induction hardening. External spur and helical gears, worm gears and internal gears, bevel gears, racks and sprockets are among the parts that are typically induction hardened (Refs. 1, 2). A sampling of parts can be seen in Figure 1. Conversely, hypoid gears and noncircular gears are rarely heat treated by induction.

Importance of Gear Material and Its Condition

Gear operating conditions, the required hardness and cost are important factors to consider when selecting materials for induction hardened gears. Plain carbon steels and low-alloy steels containing 0.40 to 0.55% carbon content are commonly specified (Refs. 1, 5). Examples include AISI 1045, 1552, 4140, 4150, 4340, and 5150. Depending on the application, tooth hardness after tempering is typically in the 48 to 60 HRC range. Core hardness primarily depends upon steel chemical composition and steel condition prior to induction hardening. For quenching and tempering, prior structure core hardness is usually in the 28–35 HRC range.

When discussing induction hardening, it is imperative to mention the importance of having "favorable" steel conditions prior to gear hardening. Hardness pattern repeatability is grossly affected by the consistency of the microstructure prior to heat treatment (referred to as microstructure of a "green" gear) and the steel chemical composition (Refs. 1, 5).

"Favorable" initial microstructure consists of a homogeneous, fine-grain, quenched and tempered, martensitic structure with hardness of 30–34 HRC; it leads to fast and consistent metal response to heat treating, with the smallest shape/size distortion and a minimum amount of grain growth. This type of initial microstructure results in higher hardness and deeper hardened case depth compared to the ferritic/pearlitic initial microstructure.

If the initial microstructure of a gear has a significant amount of coarse pearlite, and most importantly, coarse ferrites or clusters of ferrites, then these microstructures cannot be considered "favorable," because gears with such structures will require longer austenization time and/or higher austenizing temperatures to make sure that diffusion-type processes are completed and homogeneous austenite is obtained.

Ferrite is practically a pure iron and does not contain the carbon required for martensitic transformation. That's why large areas (clusters) of free ferrite require a longer time for carbon to diffuse into low-carbon regions. Actually, clusters of ferrites act as one very large grain, which often is retained in the austenite. What can result after quenching is a ferritic/pearlitic network and/or a complex ferritic/martensitic structure with scattered soft and hard spots (Ref. 1).

Steels with large carbides (i.e., spheroidized microstructures) have poor response to induction hardening

Figure 1—Typical induction hardened gears and critical components.

and also require prolonged heating and higher temperatures for austenization. Longer heat time leads to grain growth, appearance of coarse martensite, data scatter, extended transition zone and essential gear shape distortion. Coarse martensite has a negative effect on tooth toughness and impact strength, and it creates favorable conditions for cracking.

As opposed to other heat treating techniques, heat treatment by induction is appreciably affected by variation in metal chemical composition. Therefore, "favorable" initial metal condition also includes tight control of the specified chemical composition of steels and cast irons. Wide compositional limits cause surface hardness and case depth variation. Consequently, tight control of the composition eliminates possible variation of the heat treat pattern resulting from multiple steel/iron sources. Microstructurally or chemically segregated structures and banded initial microstructures of "green" gears should be avoided.

All commercial grades of steels contain limited amounts of additional chemical elements that "happened to be" in steel as traces or residual impurities in the raw materials or were added to the melting pot for the creation of certain conditions during the steelmaking process. Excessive amounts of these elements, their heterogeneous distribution and presence of appreciable-size stringers can result in stagger hardness and gear strength degradation. For example, presence of large stringers of manganese sulfide inclusions can act as stress raisers, resulting in inter-granular cracking. Sulfur level and nitrogen contents should be closely controlled.

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

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

The first step in designing an induction gear heat treatment machine is to specify the required surface hardness and hardness profile (Ref. 1).

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, spalling and can even result in some plastic deformation of the teeth (Refs. 5, 6).

A through-hardened gear tooth with a hardness exceeding 62 HRC is typically too brittle and will often experience a premature fracture. Hardened case depth should be adequate to provide the required gear tooth properties.

Figure 2 shows examples of some induction hardening patterns. An evaluation of those patterns and their effect on gear load carrying capacity and life is discussed in Reference 1.

Coil Design and Heat Mode

Depending upon the required hardness pattern and tooth

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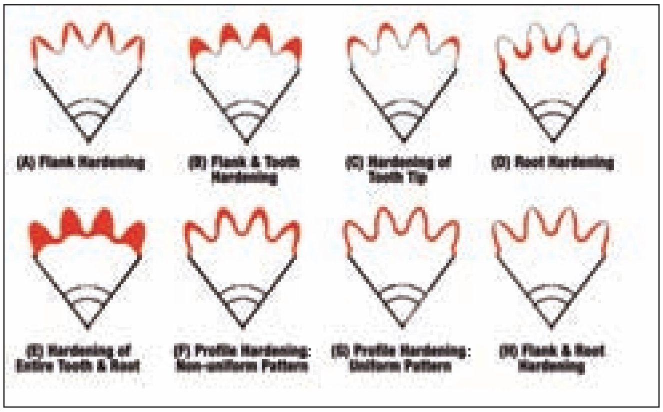

Figure 2—Induction hardening patterns.

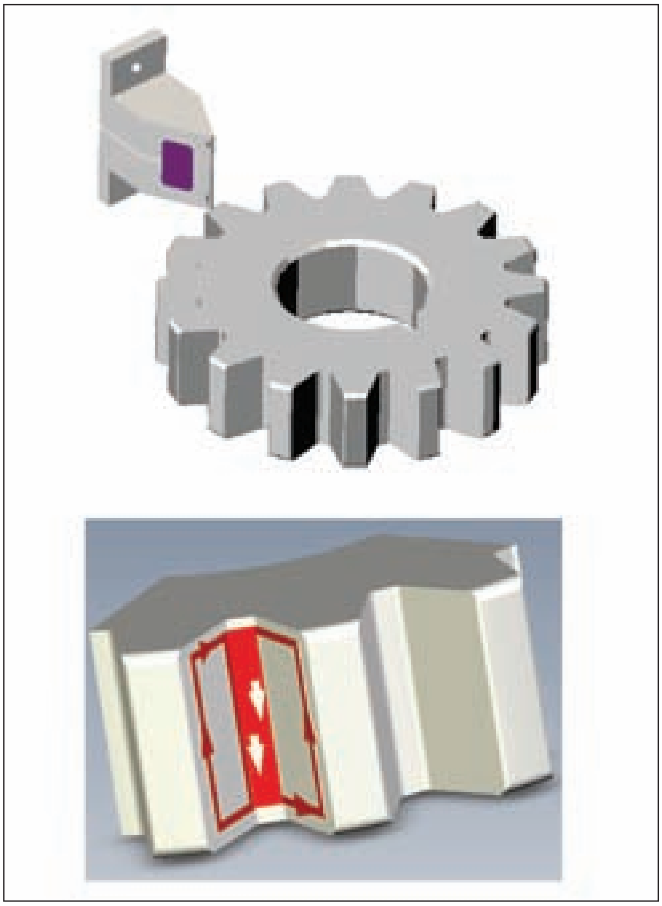

Figure 3—Gap-by-gap induction hardening.

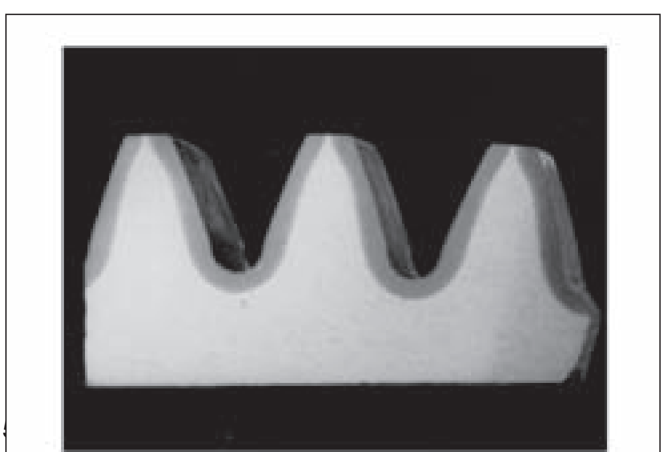

Figure 4—Typical gap-by-gap hardness pattern.

geometry, gears are induction hardened by encircling the whole gear with a coil (so-called "spin hardening of gears") or, for larger gears, heating them tooth-by-tooth with either gap-by-gap or tip-by-tip hardening (Refs. 1–4).

Tooth-by-tooth techniques—tip-by-tip and gap-by-gap hardening. These techniques can be applied using either a single-shot mode (the entire tooth or gap all at once) or by scanning. Scanning rates can be quite high, reaching 15" per minute and even higher. Both tip-by-tip and gap-by-gap techniques are typically not very suitable for small- and fine-pitch gears (modules smaller than 6).

Coil geometry depends upon the shape of the teeth and the required hardness pattern. For the tip-by-tip technique, an inductor encircles the body of a single tooth or is located around it. Such an inductor design provides patterns B and C (Fig. 2). At present time, this technique is used only for a limited number of applications.

The gap-by-gap technique is much more popular than the tip-by-tip concept. It requires the inductor to be symmetrically located between two flanks of adjacent teeth (Fig. 3). Inductors can be designed to heat only the root and/or flank of the tooth, leaving the tip and tooth core soft, tough and ductile (Fig. 4). There are many variations of coil designs applying these principles. Two of the most popular inductor designs are shown in Figure 5. Gap-by-gap inductor design was originally developed in the 1950s by the British firm Delapena.

As one can see from Figure 3, the path of the induced eddy current has a butterfly-shaped loop. The maximum current density is located in the tooth root area (the center part of the butterfly).

In most applications, the root is the most critical area of a gear because that is where the maximum concentrations of both residual and applied stresses occur. As a result, fatigue cracks and distortion occur primarily in the root area. In order to provide required heating/hardening of the root area, it is necessary to compensate a "cold sink" effect there. There is a significantly larger mass of un-heated ("cold") steel located under the gear root compared to the tooth tip or the base circle. Therefore, in order to provide a uniform heating, it is necessary to compensate an appreciable cooling effect that takes place due to thermal conduction of the massive sub-root region. A "butterfly-type" eddy current pattern does just that, allowing substantial increase of the heat sources in the gear root region and partially compensating a "cold sink" effect.

In order to further increase the power density induced in the root, a magnetic flux concentrator is applied. A stock of laminations or powder based magnetic materials is typically used as flux concentrators here. Laminations are oriented across the gap. The phenomenon of magnetic flux concentration is discussed in Reference 1.

Although the eddy current path has a butterfly shape, when combined 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. Inductor design peculiarities and application of Faraday rings help to avoid overheating.

Gears heat treated by using the gap-by-gap techniques can be fairly large, having outside diameters of 100" or more, and can weigh several tons. This technique can be applied to external and internal gears and pinions. However, there is a limitation to applying this method for hardening internal gears. Typically, it is required that the internal diameter of the gear exceed 8" and, in some cases, 10" or more.

Both tip-by-tip and gap-by-gap hardening are time-consuming processes with low production rates. Power requirements for these techniques are usually 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 is used for large gears, it could require a substantial amount of power that can diminish the cost-effectiveness of the hardening.

Applied frequencies are usually in the range of 1–30 kHz. At the same time, there are some cases when a frequency of 70 kHz and even as high as a radio frequency of 450 kHz are used.

Pattern uniformity is quite sensitive to coil positioning and its symmetrical location in a gap between two teeth. Non-symmetrical coil positioning results in a non-uniform hardness pattern. For example, an increase in the inductor-to-gear air gap 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.

Inappropriate reduction of the air gap can result in local overheating or even melting of the gear surface. Some arcing can occur between the inductor and the gear surface. Precise inductor fabrication techniques, inductor rigidity and careful alignment are required. Special locators are often 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 inductor-to-gear tooth air gap.

There can be an appreciable shape/size distortion when applying gap-by-gap technique (Refs. 1, 6). Shape distortion is particularly noticeable in the last heating position. The last tooth can be pushed out 0.1–0.3 mm. In some cases, hardening every second tooth or tooth gap can also minimize distortion. Obviously, this will require two revolutions to harden the entire gear. Therefore, final grinding is often required. There is a linear relationship between the volume of required metal removal and grinding time.

Both carburizing and nitriding operations require soaking of gears for many hours (in some cases up to 30 hours or longer) at temperatures of 850ºC to 950ºC. At these temperatures the large masses of metal expand to a much greater extent compared to a case when only the gear surface layer is heated. The expansion of a large mass of metal during heating/soaking and its contraction during cooling/quenching after carburizing results in much greater gear shape distortion compared to the distortion after induction hardening.

In addition, large gears being held at temperatures of 850ºC to 950ºC 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 serve as shape stabilizers and lead to lower, more predictable distortion.

However, due to small inductor-to-gear air gaps (0.5–1.5 mm) and harsh working conditions, these inductors require

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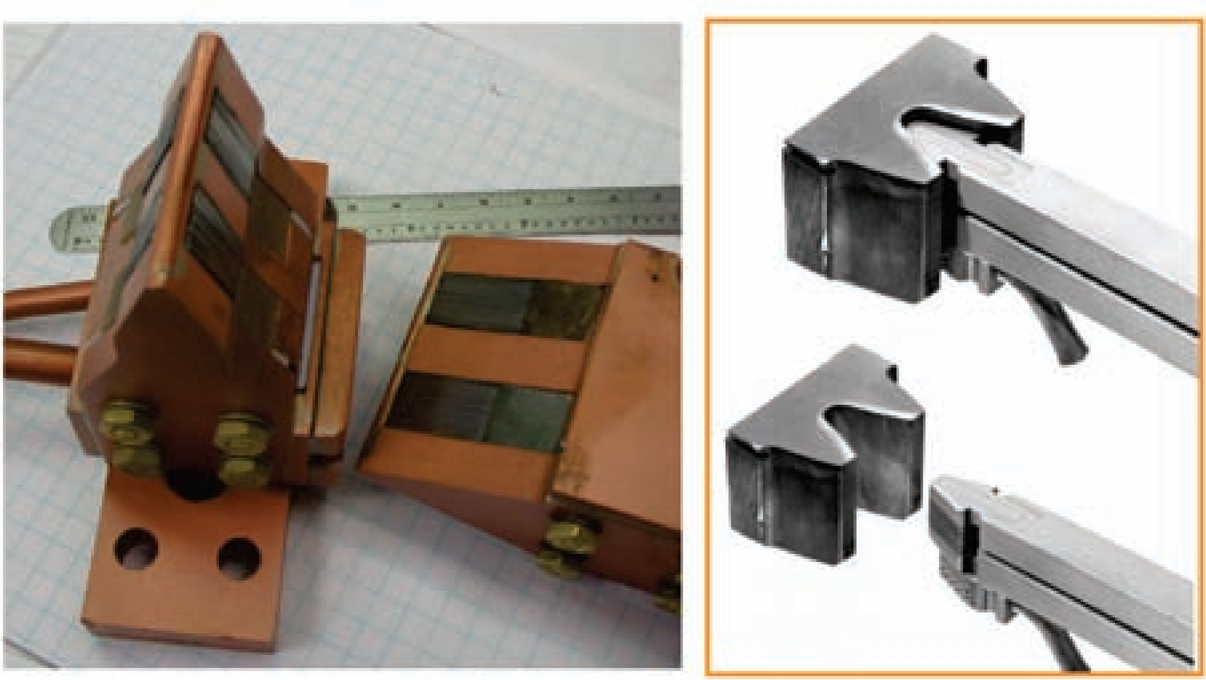

Figure 5—Gap-by-gap inductors.

intensive maintenance and have shorter life compared to inductors that encircle the gear.

Inductor copper overheating is one of the most common causes of gap-by-gap coil failure. Improper design and relatively small required inductor-to-gear gaps can lead to appreciable thermal radiation from the heated surface. This factor in combination with a limited space allowed for water cooling of the inductor can result in copper overheating, particularly when the scanning mode is used for hardening.

The gap-by-gap technique can be used in submerged hardening, where the gear is submerged in a temperature-controlled tank of quenchant. This was the basis of the original Delapena induction gear hardening process. In this method, quenching is practically instantaneous and both controllability and repeatability of the hardness pattern as well as shape stability are improved, although extra power is required. In addition, the quenchant doubles as an inductor coolant, eliminating overheating of inductor copper. In many cases of submerged hardening, an inductor does not have to be water-cooled.

Generally speaking, submerged techniques can be used in tip-by-tip hardening as well. However, as discussed above, there are a very limited number of applications requiring patterns produced by the tip-by-tip method.

Inductor failure can also be related to flux concentrator degradation (Refs. 8, 9). Laminations are exposed to harsh working conditions that could lead to their premature failure:

- High electrical currents and small space available for flux concentrators result in high power densities that could lead to a magnetic saturation of laminations and their overheating (Figure 6). The corners and end-faces of laminations tend to overheat due to electromagnetic end and edge effects (Ref. 1). Special lamination design features can be incorporated to reduce the risk of overheating.
- Laminations are sensitive to aggressive environments such as quenchants. Rust and degradation can result.

Understanding of the subtleties of tooth-by-tooth hardening allows avoiding unpleasant surprises related to premature inductor failures and allows the design of repeatable and long-lasting inductors.

When developing gap-by-gap hardening, 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 has approximately the same length as the gear width. A single-shot mode is more limited in providing a uniform face-to-face hardness pattern compared to scanning mode.

When applying the scanning mode for hardening gears with wide teeth, two techniques can be used. The first technique represents a design concept where the inductor is stationary and the gear is moveable. The second concept assumes that the gear is stationary and the inductor is moveable.

For the scanning mode, the inductor length is typically at least two times shorter than the gear thickness. In order to obtain the required face-to-face temperature uniformity, it is necessary to use a complex control algorithm: "Power and Scan Rate vs. Inductor Position." A short dwell at the initial and final stages of inductor travel is often used. Thanks to preheating due to thermal conductivity, the dwell at the end of the heat cycle is usually shorter, compared to the dwell at the beginning of travel.

Undesirable Tempering Back

One typical concern when applying tip-by-tip or, in particular, gap-by-gap hardening techniques is the problem of undesirable heating of the areas adjacent to the hardened area (tempering back). Concern of a tempering back is particularly pronounced for Patterns A, D and I when using gap-by-gap hardening (Fig. 7a). There are two main reasons why an undesirable tempering back can take place (Ref. 1).

The first reason deals with the external magnetic field coupling phenomena of the inductor. The application of magnetic flux concentrators to the inductor 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. Applying thin copper shields can also reduce the undesirable heating of adjacent teeth.

The second reason deals with thermal conductivity phenomena. Heat is transferred by thermal conduction from a high-temperature region of the gear towards 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, there is a danger that the opposite side of the gear tooth will be heated by thermal conductivity to an inappropriately high temperature, which will result in undesirable tempering back of previously hardened areas.

Whether a hardened side of a tooth will in fact be softened due to tempering back depends upon the applied frequency, gear module, tooth shape, heat time and hardness case depth. In the case of shallow and moderate case depth and large teeth, the root of the tooth, its fillet and bottom of the tooth flank are typically not overheated due to a 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 "troubled areas" as far as tempering back is concerned (Fig. 7a). This 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.

In order to overcome the problem of tempering back, additional cooling blocks can be used. Additional cooling protects already hardened areas while heating unhardened areas of the gear (Fig. 7b). Even though external cooling is applied, depending on the tooth shape and process parameters, there still may be some unavoidable tempering back. This tempering back is typically insignificant and acceptable.

If submerge hardening is used, the fact that a gear is submerged in quenchant helps to prevent tempering back problems as well.

Conclusions

Induction hardening of gears is an important heat treating technique that can be applied to a wide range of gears and other parts, especially internal and external spur, helical and bevel gears, allowing manufacturers precise control over case depth and microstructure for increased load carrying capacity and other properties.

For best results in induction hardening, manufacturers must ensure the proper initial condition of the gear material, including chemical composition and microstructure.

Tooth-by-tooth (tip-by-tip and gap-by-gap) methods are often used for larger gears. The methods were described, along with various process and inductor design subtleties.

Part II of this article, which will appear next issue, will discuss spin-hardening of gears and gear-like components, in which the inductor coil encircles the gear. Part II will also cover various process concepts that can be employed with spin hardening.

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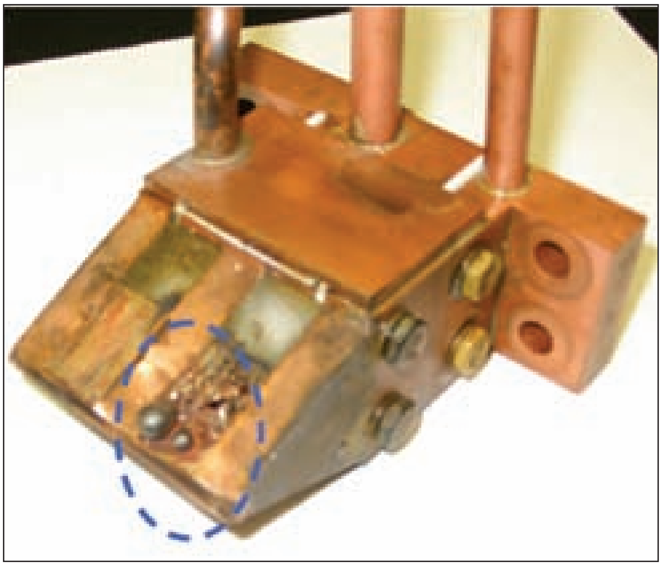

Figure 6—Typical coil failure of a gap-by-gap inductor.

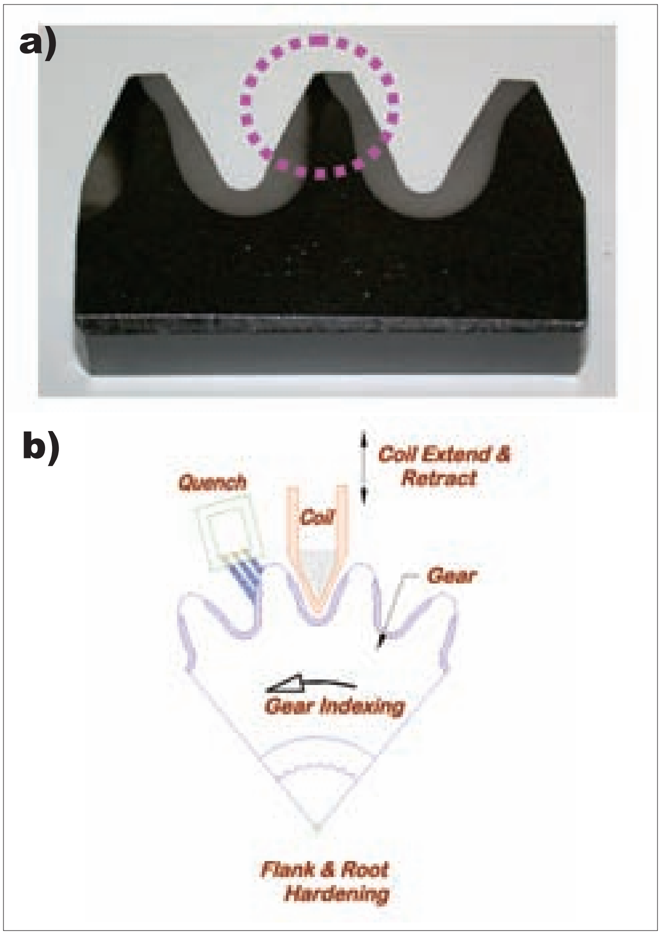

Figure 7—Tempering back effect and its control. a) Undesirable tempering back; b) To overcome undesirable tempering back of previously hardened tooth, cooling blocks are added.

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