The "Metallurgical Notch" in Type B Induction Hardened Gears

By Robert Errichello, Andrew Milburn and Rainer Eckert

Introduction

Induction hardening is often used for large gears that are too large for existing carburizing furnaces. Large gears are usually heat treated by the tooth-to-tooth scanning induction hardening process, and that is the subject of this report. A major advantage of induction hardening is that the distortion and growth is much less than that associated with carburizing because only the case is heated while the core remains below the transformation temperature. However, induction-hardened gears have lower surface hardness and less load capacity than carburized gears, and this limitation must be recognized in any comparison of carburized and induction-hardened gears.

Advantages of Induction Hardening Over Carburizing

Induction hardening offers many advantages (Ref. 1):

- Capable of heat treating large gears
- Less distortion and shape change than carburizing
- Short process time maximizes productivity
- Repeatable quality with proper quality control
- Efficient process saves energy costs
- Environmentally friendly
- Any smoke or fumes are easily removed
- Significant reduction of heat exposure
- Significant reduction of scaling and decarburization
- Far less startup and shutdown time lowers labor cost
- Reduced maintenance costs
- Less floor space required

Disadvantages of Induction Hardening

Induction hardening has several possible pitfalls (Refs. 2–3).

- Less load capacity than carburized gears
- Back tempering
- Root and flank cracking
- Melting and overheating
- Unhardened areas
- Uneven hardening patterns
- Distortion and growth
- Heat treat parameters are difficult to control and heat treating defects are difficult to detect

Manufacturing considerations and pitfalls for induction hardening. Quoting from Ingham and Parrish (Ref. 2), "Induction hardening has problems. In the wrong heat treater's hands, the results can be disastrous." Quoting from Midea and Lynch (Ref. 3), "Any number of relatively minor variations can force the hardening process out of specification. Proper operator training, adequate maintenance and a fundamental understanding of the hardening process are all part of the equation. For induction hardening of gears, the devil is in the details."

Figure 1 shows a tooth from an induction-hardened gear that failed by bending fatigue because the hardened pattern did not include the full contour of the root fillet. There were 89 teeth on the gear and all teeth failed in an identical manner.

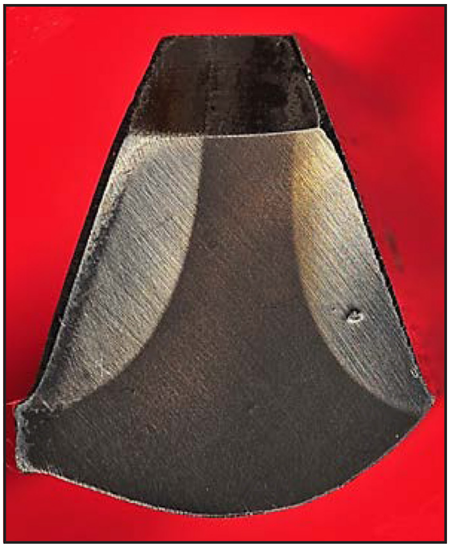


Figure 1 Bending fatigue failure of induction-hardened gear.

A classic bending fatigue crack started in the right root fillet at the point where the induction- hardened pattern emerged at the surface of the root fillet. AGMA 2101 (Ref. 4) classifies this as type B flank hardening and allows only $_{\sigma FP} = 150$ N/mm^2 bending stress instead of the usual 380 N/mm^2 for type A hardening pattern where the entire root fillet is hardened. Therefore, type B flank hardening has only 39% of the bending strength of a type A hardening pattern. Furthermore, AGMA 2101 (Ref. 4) allows $_{\sigma FP} = 485$ N/mm^2 for a carburized gear. Therefore, an induction hardened gear with a type B hardening pattern has only 31% of the bending strength of a carburized gear. Therefore, to have any chance of competing with a carburized gear, an induction-hardened gear must have a full contour (type A) hardening pattern, which would allow 78% of the bending strength of a carburized gear.

Figure 2 (taken from Fig. 8 of (Ref. 2)) shows a typical residual stress profile at the root of an induction-hardened gear. It shows that there are high compressive residual stresses at the surface and through the case hardened zone, which are beneficial because compressive residual stresses increase both macropitting resistance and bending fatigue resistance. However, there are detrimental tensile residual stresses that exist below the case/core boundary that peak at a depth of about twice the effective case depth. This is a critical area that can initiate subcase fatigue cracks, especially if nonmetallic inclusions are in the area of tensile residual stresses. Therefore, material cleanliness must be carefully controlled to avoid subcase fatigue or subsurface initiated bending fatigue. See ANSI/AGMA 1010-F14 (Ref. 5) for more information on these failure modes.

With type B hardening pattern the residual tensile stresses occur at the surface of the root fillet where they dramatically increase the risk of bending fatigue. Hence, metallurgists call the run-out of the hardened layer a "metallurgical notch." Figure 3 (taken from Fig. 19, (Ref 2)) shows the mechanism of a "metallurgical notch."

Uneven hardening pattern. Ideally,

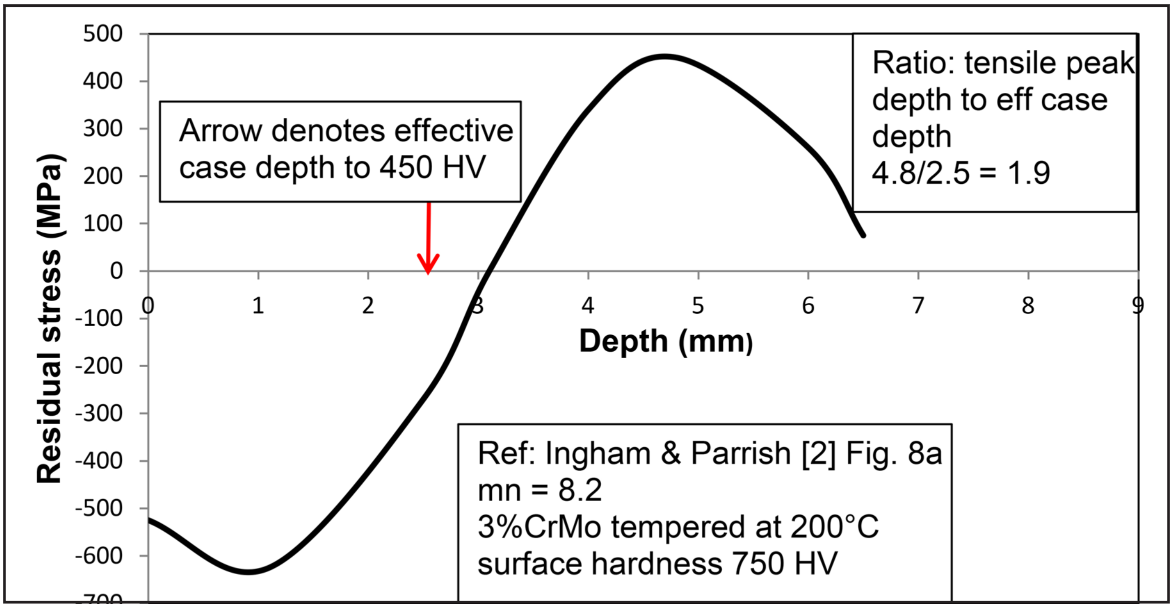


Figure 2 Induction-hardened residual stress profile (Ref. 2).

the inductor should be positioned symmetrically between the flanks of two adjacent teeth and at the correct depth. Asymmetrical inductor alignment, incorrect depth within the tooth space, or inadequate inductor rigidity, can result in uneven hardening patterns with excessive case depth on one flank and inadequate case depth on the adjacent flank. Figure 1 shows that the failed gear had a deeper case depth on the left flank than on the right flank.

Back tempering. As a tooth space is heated to temperatures above 720°C, some heat conducts through the teeth where it results in back tempering of previously hardened teeth. Therefore, a certain amount of softening by back tempering is inevitable, which can cause a loss of hardness that can range from a few points HRC to over 10 HRC (Ref. 3). Therefore, back tempering must be controlled by an adequate flow of quenchant to avoid excessive softening. The tooth tip and topland are critical areas for back tempering because there is a relatively small mass of metal at the tooth tip and there is a short distance for heat to travel from the heated flank to the previously hardened flank. To avoid back tempering,

This paper was originally prepared for the AGMA Metallurgy Committee. It was submitted with the recommendation to include the following definition to the next edition of AGMA 923: Metallurgical notch: If an induction hardened gear with type B flank hardening has a pattern that terminates (runs out) at the surface of the root fillet it is accompanied by tensile residual stress that adds to the bending stress, which greatly reduces the bending fatigue resistance. This is known as a "metallurgical notch."

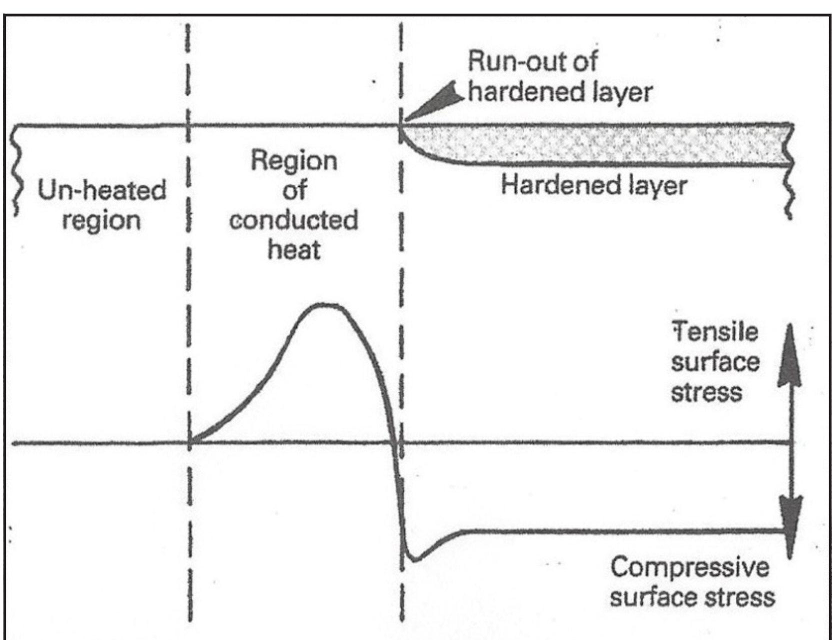


Figure 3 Residual stresses at end of hardened layer (Ref. 2).

additional cooling can be used on the previously hardened flank. Figures 4a and 4b (taken from Figs. 3a and 3b of reference (R3)) demonstrate how cooling jets can help prevent back temper. See reference 3 for guidelines to minimize back tempering.

Unhardened areas. Electromagnetic edge effects where the inductor enters or leaves the tooth space can result in areas that are left unhardened. Therefore, parameters such as how far the inductor is introduced into the tooth space before energizing, how long it dwells there in the energized state before starting its heating traverse, and how long it dwells at the end of the traverse must be closely controlled to avoid unhardened areas. Furthermore, the power density and traverse rate versus inductor position must be closely controlled. Within hardened areas the residual stresses are compressive, but in unhardened areas there are tensile residual stresses. Consequently, unhardened areas are defects that have very low bending fatigue resistance. Figure 5 is an example that shows unhardened areas near the end of the teeth (Fig. 18, Ref. 2).

Generally, induction-hardened gears are not as reliable as carburized gears because there are many more heat treating parameters that are difficult to control, and the manufacturing defects are difficult to detect. The most frequent root cause of failure of induction-hardened gears is inadequate case depth in the root fillet (for example, see Figs. 1 and 5). When the hardness pattern terminates (runs out) at the surface of the root fillet it is accompanied by tensile residual stresses (see Fig. 3), which often culminate in a bending fatigue failure. It is imperative to recognize that if a gear design requires a type A pattern, and a type B is manufactured, the gear will fail in service.

Definition for "metallurgical notch." Metallurgical notch: If an induction hardened gear with type B flank hardening has a pattern that terminates (runs out) at the surface of the root fillet it is accompanied by tensile residual stress that adds to the bending stress, which greatly reduces the bending fatigue resistance. This is known as a "metallurgical notch."

Figure 4a Induction hardening with cooling jets turned off (Ref. 3).

Figure 4b Induction hardening with cooling jets turned on (Ref. 3).

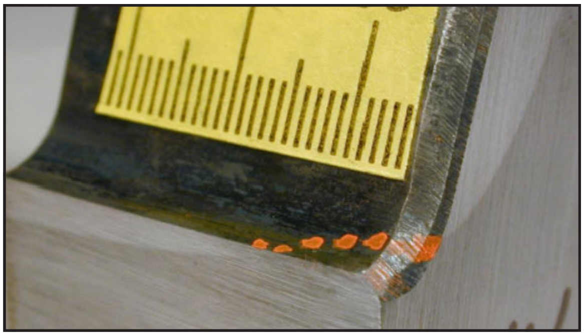


Figure 5 Unhardened area at end of tooth.

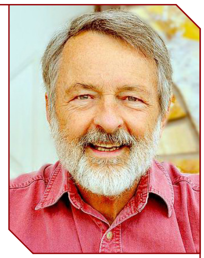
Conclusions

1. Induction hardening offers significant advantages over carburizing such as less distortion, higher productivity, environmental friendliness, and lower costs.
2. Induction-hardened gears have less load capacity than carburized gears. This limitation must be recognized in any comparison of carburized and induction- hardened gears.
3. Induction hardening has several possible manufacturing pitfalls including back tempering, root and flank cracking, melting and overheating, unhardened areas, uneven hardening patterns, and distortion and growth.
4. Induction-hardened gears are not as reliable as carburized gears because there are many more heat treating parameters that are difficult to control, and heat treating defects are difficult to detect.
5. If a gear design requires a type A flank hardening pattern, and a type B is manufactured, the gear will fail in service.
6. Type B flank hardening pattern is an example of a "metallurgical notch."
7. Type B flank hardening has only 39% of the bending strength of a type A hardening pattern.
8. Type B hardening pattern has only 31% of the bending strength of a carburized gear.

References

1. Rudnev, V., et al., "Handbook of Induction Heating," Marcel Dekker, Inc. (2003).
2. Ingham, D.W., and G. Parrish. "The Submerged Induction Hardening of Gears," ***Gear Technology***, March/April, (2001) pp. 28–40.
3. Midea, S.J., and D. Lynch. "Tooth-by-Tooth Induction Hardening of Gears (and How to Avoid Some Common Problems)," *Thermal Processing*, April 17, (2014) pp. 46–51.
4. ANSI/AGMA 2101-D04. "Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth," AGMA (2004).
5. ANSI/AGMA 1010-F14. "Appearance of Gear Teeth-Terminology of Wear and Failure," AGMA (2014).

For Related Articles Search
Induction Hardened Gears
at www.geartechnology.com



Robert Errichello is founder of GEARTECH. He has over 50 years of industrial experience and has taught courses in material science, fracture mechanics, vibration, and machine design at San Francisco State University and the University of California at Berkeley. He presented seminars on design, analysis, lubrication, and failure analysis of gears and bearings to professional societies, technical schools, and gear, bearing, and lubrication industries. He is a graduate of the University of California at Berkeley and holds BS and MS degrees in Mechanical Engineering and a Master of Engineering degree in structural dynamics. Bob is a member of the AGMA Gear Rating Committee, AGMA/AWEA Wind Turbine Committee, ASM International, ASME Power Transmission and Gearing Committee, STLE, NREL GRC. Bob has published over 100 articles on design, analysis, and application of gears. He is technical editor for GEAR TECHNOLOGY and STLE Tribology Transactions. He is recipient of the AGMA TDEC Award, AGMA E.P. Connell Award, AGMA Lifetime Achievement Award, STLE Wilbur Deutch Memorial Award, STLE Edmond E. Bisson Award, and AWEA Technical Achievement Award.

Andy Milburn is currently president of Milburn Engineering, Inc., a consulting firm located near Tacoma, Washington and has 45 years experience in the design and analysis of gears and gearboxes. Prior to starting his own consulting firm in 1989 he worked at The Gear Works in Seattle, WA for 15 years and was involved in all aspects of gear manufacturing, gear failure analysis and designed many custom industrial gearboxes. As a consultant he has investigated numerous gear and bearing failures, and helped clients improve their gear products. During the past 18 years he has been very active in the wind industry investigating gearbox failures, developing gearbox modifications and participating in due diligence design reviews. He was a U.S. delegate to ISO TC66, working on the new international gearbox standard, IEC 81400-4. He is a registered Professional Engineer in the state of Washington, a member of AGMA, ASME, ASM and STLE and a member of the AGMA Helical Gear Rating Committee. Milburn is currently one of the moderators of the AGMA Gear Failure Analysis course.

Rainer Eckert is a forensic engineer and director of the metallurgical services department for Simon Forensic, LLC in Seattle, WA. In that role he has conducted several thousand failure analyses of industrial components and has served as an expert witness in several hundred court cases. Eckert has also assisted manufacturers in basic research, design improvement, quality control, and root cause failure analysis. His expertise also extends to wind turbines, thus he serves as Simon Forensic's technical advisor to domestic and international wind turbine manufacturers. Eckert holds a BS in science and engineering (1983) from the Technical University of Berlin; a BS of science and engineering in welding engineering (1983) from the Welding Institute of Berlin; and a Masters of science and engineering in materials science (1985) from the University of Pennsylvania. As a graduate research assistant there, he studied monotonic and cyclic fracture (fatigue) behavior of various copper alloys by means of optical microscopy, scanning electron microscopy (SEM) and auger spectroscopy. He has authored a number of technical papers for various associations such as AGMA and STLE. And finally, and of equal importance, Eckert is one damned good auto mechanic.