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REDUCING GEAR SIZE FOR COMPACT TRANSMISSION DESIGN USING COMPUTER MODELING

Zhichao (Charlie) Li, B. Lynn Ferguson, and Andrew Freborg

Modeling shows that reducing the gear size can still produce the required performance with proper material selection and heat treatment.

KEYS TO LONG-LASTING HARDENING INDUCTORS: EXPERIENCE, MATERIALS, AND PRECISION

Valery Rudnev, Aaron Goodwin, Steven Fillip, William West, Jim Schwab, and Steve St. Pierre

Advanced designs and precise fabrication can ensure long inductor coil life while producing high-quality treated parts.

TECHNICAL SPOTLIGHT: ULTRAFAST BORIDING: A TRANSFORMATIONAL TECHNOLOGY

Ali Erdemir

An industrial-scale boriding process can drastically reduce costs, increase productivity, and improve the performance and reliability of a variety of machine parts.

EDITORIAL OPPORTUNITIES FOR HTPro IN 2015

The editorial focus for HTPro in 2015 reflects some key technology areas wherein opportunities exist to lower manufacturing and processing costs, reduce energy consumption, and improve performance of heat treated components through continual research and development.

November

Atmosphere/Vacuum Heat Treating

To contribute an article to one of the upcoming issues, contact Frances Richards at frances.richards@asminternational.org.

To advertise, contact Erik Klingerman at erik.klingerman@asminternational.org.

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ABOUT THE COVER

Industrial parts are removed from ANL’s large-scale ultrafast boriding furnace after treatment. Courtesy Argonne National Laboratory, www.anl.gov.
Heat Treat 2015 is right around the corner. With today’s rapid advancements in heat treating equipment and process technology, it’s extremely important to stay abreast of these developments to ensure that your company maintains the highest level of competitiveness. Thomas Friedman, in his book *The World is Flat*, says that globalization is happening at a lightning pace and that countries, companies, communities, and individuals must adapt to this “flattening” of the globe. Disruptive technologies require an organization that is ready, willing, and capable of supporting them. The Heat Treating Society’s premier heat treating conference and exposition provides an opportunity to learn about some of the latest developments in the industry to stay at the leading edge of heat treating-related technology.

The Heat Treating Society (HTS) is the world’s largest network of heat treaters with a worldwide membership of commercial and captive heat treaters, equipment manufacturers, leading academic and government researchers, and technical experts from various industries. The collective knowledge of HTS members is invaluable. The Society offers a venue to network with these experts, share insights, and build life-long friendships. HTS members also can serve as mentors to young academicians, engineers, and practitioners, laying the foundation for future generations. There is vast experience that resides with longtime members who will be retiring over the next 10-15 years. This needs to be captured and passed on, lest it be lost to later generations. Participation in the Society affords the opportunity to both share and gain this knowledge.

Consider joining HTS for the educational and networking opportunities and stay for the fun! If you are already a member, or are becoming a new member, get involved, get connected, and get ahead by becoming a HTS volunteer. Remember, volunteerism should be fun! It must be about the people, and it’s very rewarding to gain and give knowledge while building relationships. Stop by the Heat Treating Society booth at the show, and see how you can benefit from active membership and participation.

I hope to see you in Detroit!

Stephen G. Kowalski
President, ASM Heat Treating Society

Busted!
This company’s QA program AND reputation

Like Humpty Dumpty, it is hard to put the pieces back together once a real world product quality disaster strikes. The ultimate cost of a recall will be far, far greater than any savings from cutting corners or not investing in a quality assurance program in the first place. With our broad spectrum of physical testing machines, software, and technical support, Tinius Olsen can help you assure quality from material to end product. To international standards and your toughest specifications. Reputations (yours and ours) depend on it.
HTS NAMES NEW BOARD MEMBERS FOR 2016

The Heat Treating Society (HTS) board, at the recommendation of the HTS Awards and Nominating Committee, named new officers including Jim Oakes to serve as vice president for the 2015–2017 term; Nathan Chupka, Michael Pershing, and Craig Zimmerman, to serve on the HTS Board for the 2015–2018 term; Olga Rowan for the 2015–2016 term (filling the unexpired term of Jim Oakes); Rachel Sylvester to serve as student board member for the 2015–2016 term; and Hannah Noll to serve as young professional board member for the 2015–2016 term. Terms begin September 1. Continuing on the board are Timothy De Hennis (member), Eric Hutton (member), Stephen Mashl, FASM (member), Jin Xia (member), and Zbigniew Zurecki, FASM (member). Roger Jones becomes past president and Stephen Kowalski becomes president on September 1. Leaving the board are Thomas Clements (past president), William Disler (member), Robert Goldstein (member), Richard Howell (member), Piyamanee Komolwit (young professional board member), and Lee Rothleutner (student board member).

Stephen Kowalski is president of Kowalski Heat Treating Co., Cleveland, assuming the position in 1997 for the second-generation family business. He earned his B.Sc. degree in business administration from Miami University in 1984. Kowalski is a member of the Metal Treating Institute and was a founding member of the ASM Heat Treating Society. He served on the HTS board from 2003–2010, served as chair of the HTS Membership Committee from 2006–2013, and also served as chair of the ASM Membership Committee from 2012–2013. Kowalski has served on many nonprofit boards working to enhance private and public partnerships. He has also worked with local, state, and national employment organizations to develop and implement training programs to enhance worker retention rates. Kowalski published several papers on furnace systems controls, high-pressure gas quenching, and government financing of business development.

Jim Oakes is vice president of business development for Super Systems Inc. (SSI), Cincinnati. Since joining SSI in 2005, Oakes has overseen marketing, helped develop product innovation strategies, and drives SSI’s commitment to quality and continuous improvement in the company’s heat treating-related products. Prior to joining SSI, he worked at Oracle Corp., Redwood City, Calif., helping organizations leverage technology to become more competitive and improve processes with enterprise software solutions. Oakes serves on the Metal Treating Institute board and is a member of several committees focused on bringing value back to the members. He has been involved with ASM for many years at the local chapter level and contributed to the revised ASM Handbook on heat treating.

Nathan Chupka is manufacturing engineering supervisor for the gear and shaft manufacturing operations at John Deere Waterloo Works. He started at John Deere in 1998 as a materials engineer and became manufacturing engineer in 2001 for the carburizing, carbo-nitriding, press quenching, and tempering operations, as well as development and implementation of heat treatment processes for drivetrain components. He was involved with the startup of a new automated batch carburizing facility and press quench operations from 2003–2006. In 2005, he became manufacturing engineering supervisor for heat treat operations. Recent activities involve developing heat treat training programs, supporting equipment installation for new product introductions and capacity expansion, and developing new heat treating technology. Chupka has been a member of ASM since 1995 and a member of the Northeast Iowa Chapter since 1998. He has served as chair and vice chair for the local chapter.

Michael Pershing held positions at Caterpillar in heat treat engineering, casting simulation development, and gear materials before becoming team leader for heat treat R&D in 1998. Pershing worked at Caterpillar’s Powder Metal Focus Facility in Rockwood, Tenn., from 2000–2003, then joined the Oak Ridge National Laboratory Materials Processing Group for three years before returning to Caterpillar’s Engine Materials Technology group in 2006. He was engineering manager for East Peoria’s Heat Treat Engineering for three years, and now is senior heat treat technology steward. Pershing has been involved with the Center for Heat Treating Excellence, WPI, Worcester, Mass., since 2007, was board chairman from 2012–2014, and received the CHTE Distinguished Service Award in 2014. He also held several leadership positions in the Peoria and Oak Ridge ASM Chapters, including Peoria Chapter chair for 2008–2009.
Craig Zimmerman started his career in heat treating in 1994 at FPM Heat Treating, Milwaukee, working as a second shift lab technician. He then joined Lindberg Heat Treating (acquired by Bodycote Thermal Processing), working eight years at Bodycote’s Melrose Park, Ill., facility in several positions including chief metallurgist, quality manager, and both business unit and plant manager. He was promoted to Bodycote’s regional staff and served as a regional sales manager-central group and director, technology development-the Americas from 2002–2010. Zimmerman joined Bluewater Thermal Solution in 2010, and is currently corporate director-technical, serving as a technical resource for staff and customers, developing and commercializing new technologies, and improving existing company heat treat technologies. He is also an expert in boronizing/boriding technology. Zimmerman is an active member and past chairman of the ASM HTS Research & Development Committee.

Olga (Olly) Rowan is senior engineer in Advanced Materials Technology, Caterpillar Inc. Rowan was a member of the Center for Heat Treating Excellence, WPI, Worcester, Mass., from 2004–2007, working on gas carburizing atmosphere optimization. She joined Caterpillar in 2007 working in heat treat R&D, NPI, gear heat treat production support, and supplier development. Her areas of expertise include gas atmosphere and vacuum heat treat, energy and business case analysis for new capital introduction, and heat treat process control and optimization. She is a member of ASM, active in the Peoria chapter and on the national level. She was a member of the ASM Emerging Professionals Committee for five years and a member of the ASM Education Committee for four years. She also serves as an ASM Materials Camp organizer and mentor in the Central Illinois area. Rowan co-authored two articles in Steel Heat Treating Fundamentals and Processes, Vol 4A, ASM Handbook, and has published 18 peer-review journal articles and conference publications and 16 internal technical reports.

Rachel Sylvester is currently a senior at The Ohio State University in the materials science & engineering program, and serves as lead teaching assistant for the first year engineering program. She completed an internship with Cessna Aircraft in metallurgical failure analysis, and is currently interning with Ford Motor Co. in the same capacity. Sylvester attended ASM Materials Camp in 2011 and has been an ASM member since then, currently serving as vice president for the Ohio State Chapter of Materials Advantage. She served as a junior member twice, and traveled to a Materials Camp in Clermont-Ferrand, France. Sylvester is a recipient of the George A. Roberts Scholarship.

Hannah Noll earned her B.Sc. in metallurgical engineering from Missouri University of Science and Technology in 2010, and is pursuing an M.S. in materials science and engineering at North Carolina State University. After graduating from Missouri S&T, she joined ATI Specialty Materials as product engineer, and is currently process engineer at ATI Specialty Materials Richburg Operations responsible for Ni/Ti/Fe-base alloy heat treatment, continuous bar rolling, and coil processing. She is responsible for qualifying equipment and process improvements for materials used primarily in the aerospace, biomedical, and oil & gas industries. Noll has been a member of the executive board of the ASM Carolinas Southern Piedmont Chapter since 2012 and is currently chapter chair. She is a contributing member of engineergirl.org, directed the first Union County JobReady Partnership “Women in Engineering” summer camp for middle school girls in 2014, and will direct the camp in 2015.

ROWAN RECEIVES 2015 ASM HTS/SURFACE COMBUSTION EMERGING LEADER AWARD

Established in 2013, the ASM HTS/Surface Combustion Emerging Leader award recognizes an outstanding early-to-midcareer heat treating professional whose accomplishments exhibit exceptional achievements in the heat treating industry. The award acknowledges an individual who sets the highest standards for ASM Heat Treating Society participation and inspires others to dedicate themselves to the advancement and promotion of vacuum and atmosphere heat treating technologies such as carburizing, carbonitriding, nitriding, annealing, and through hardening. The award will be presented at the HTS General Membership Meeting on Wednesday, October 21, at the ASM Heat Treating Society Conference and Exposition in Detroit.

Olga (Olly) Rowan, senior engineer in Advanced Materials Technology, Caterpillar Inc., is recognized “for a strong combination of extensive carburizing expertise, passion for advancing the science of heat treatment, and recognized leadership.”
Virtual Tour

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This video showcases the inner-workings of the heat zone, combustion system, quench tank, controls, loader and more – all of which allow the single-chain model to deliver precision and versatility through incredibly advanced, energy-efficient controls and ease of integration. Other features include:

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HTS MEMBERS IN ASM’S 2015 CLASS OF FELLOWS

In 1969, ASM established the Fellow of the Society honor to provide recognition to members for their distinguished contributions to materials science and engineering and to develop a broad-based forum of technical and professional leaders to serve as advisors to the Society. Awards will be presented at ASM’s annual Awards Dinner, Tuesday, October 6, in Columbus, Ohio, during Materials Science & Technology 2015.

Dr. Joseph W. Newkirk, FASM, associate professor, Missouri University of Science and Technology, Rolla, is recognized “for outstanding contributions in teaching, mentoring, professional service, and entrepreneurial research in alloy property development, particulate composites, powder metallurgy materials, and property assessment of powder metallurgy and metal injection molded parts.”

Prof. Yongho Sohn, FASM, professor, University of Central Florida, Orlando, is recognized “for significant contributions to teaching and research in the fundamental understanding of multi-component diffusion kinetics, analysis and control of microstructures, phase transformations, and the application of advanced materials characterization techniques.”

Prof. Chester J. Van Tyne, FASM, FIERF professor, Colorado School of Mines, Golden, is recognized “for significant contributions to understanding the effects of processing and microstructure on the plastic deformation behavior of steels and nickel-base alloys in metal-forming manufacturing processes.”

Mr. Zbigniew Zurecki, FASM, senior research associate, Air Products & Chemicals Inc., is recognized “for conceptualization and sustained development of cleaner, safer, and environmentally friendlier alternatives to many conventional methods of processing metals resulting in improved product quality and increased productivity of industrial operations.”

HTS MEMBERS RECEIVE ASM 2015 AWARDS

The awards program recognizes achievements of members of the materials science and engineering community. Awards will be presented at ASM’s annual Awards Dinner, October 6, in Columbus, Ohio, during MS&T15.

Distinguished Life Membership was established in 1954 and is conferred on leaders who have devoted their time, knowledge, and abilities to the advancement of the materials industries.

Mr. Richard L. Wilkey, president, Fisher-Barton Group, Waukesha, Wis., will receive this year’s award “for the entrepreneurial drive in business creation and growth and persistent and aggressive advancement in materials science and engineering and the people and industries who use them.”

WILLIAM HUNT EISENMAN AWARD

The William Hunt Eisenman Award was established in 1960, in memory of a founding member of ASM, and its first and only secretary for 40 years. It recognizes unusual achievements in industry in the practical application of materials science and engineering through production or engineering use.

Dr. Frederick E. Schmidt, FASM, senior managing consultant and director, materials technology, Engineering Systems Inc., Aurora, Ill., will receive this year’s award “for pioneering industrial developments in electronics, polymer, and chemical processing, wear and corrosion problems, and especially the reduction of scrap in small caliber ammunition production.”

BEST PAPER IN HEAT TREATING CONTEST

The ASM HTS/Bodycote award was established by HTS in 1997 to recognize a paper that represents advancement in heat treating technology, promotes heat treating in a substantial way, or represents a clear advancement in managing the business of heat treating. The award is endowed by Bodycote Thermal Process-North America.

The contest is open to all students, in full-time or part-time education, at universities (or their equivalent) or colleges. It is also open to those students who have graduated within the past three years and whose paper describes work completed while an undergraduate or post-graduate student. The winner receives a plaque and check for $2500.

To view rules for eligibility and paper submission, visit the Heat Treating Society website at hts.asminternational.org/portal/site/hts/HTS_Awards. Paper submission deadline is December 11. Submissions should be sent to Joanne Miller, ASM Heat Treating Society, 9639 Kinsman Rd., Materials Park, OH 44073, 440.338.5151 ext. 5513, joanne.miller@asminternational.org.
Innovation

ECM Technologies and ECM USA have installed over 1000 cells of heat treating capacity with almost every Automotive company in the world. These systems provide low pressure vacuum carburizing and gas quenching for millions of parts that bring motion and reliability into our daily lives. From automatic, manual transmissions, dual clutch, CVT, to axles and even airplane engine parts, ECM and our processes are part of your lives. Let us build a system for you.

- Vacuum Carburizing
- Gas Quenching
- Oil Quenching
- Carbonitriding
- Neutral Hardening

VISIT US AT ASM’S HEAT TREAT 2015 OCT. 21-22, 2015: BOOTH 420
HEAT TREATING ADDITIVELY MANUFACTURED ALLOYS

Applications in additive manufacturing (AM), also known as 3D printing, are growing, especially in the biomedical industry where individually customized parts such as hip joints, knee replacements, and dental applications are in high demand. The Center for Heat Treating Excellence (CHTE) at Worcester Polytechnic Institute (WPI), Mass., is studying the best way to heat treat these parts for optimum performance.

“Because these components become a part of our bodies, we need to determine how to post-process them to remove defects that can initiate fatigue fractures, resulting in a deterioration in the mechanical properties of the material,” says Richard Sisson, WPI professor of mechanical engineering and technical director of CHTE.

Titanium and titanium alloys, cobalt alloys, and stainless steels are the four main types of metallic biomaterials. Titanium alloys are preferred in dental and orthopedic implants due to their good mechanical properties, biocompatibility, lack of allergic reaction, and excellent corrosion resistance.

WPI graduate student Yangzi Xu, under the direction of Sisson, is investigating the effects of heat treatment on the microstructure, mechanical properties, and corrosion behavior of additively manufactured Ti-6Al-4V titanium alloy parts fabricated using the direct metal laser sintering (DMLS) process. DMLS uses a laser as the power source to sinter successive layers of metal powder based on a computer-aided design. The technique binds the material together to create a solid structure. Three post heat treatments being investigated include solution treatment and aging, stress relieving, and annealing.

Evaluation of parts includes measuring microindentation hardness, determining microstructure and phase evolution using scanning electron microscopy and x-ray diffraction, and electrochemically measuring corrosion behavior in simulated body fluid at a temperature of 37°C (98.6°F). Research results of the study are expected in 2016.

ABOUT CHTE

The CHTE collaborative is an alliance between the industrial sector and university researchers to address short-term and long-term needs of the heat-treating industry. Membership in CHTE is unique because members have a voice in selecting quality research projects that help them solve today’s business challenges.

Research projects are member driven. Each research project has a focus group comprising members who provide an industrial perspective. Members submit and vote on proposed ideas, and three to four projects are funded yearly. Companies also have the option of funding a sole-sponsored project. In addition, members own royalty-free intellectual property rights to precompetitive research and are trained on all research technology and software updates.

CHTE projects now in progress include:
- Nondestructive Testing for Hardness and Carburization
- Improving Furnace Alloys and Fixtures
- Gas Quench Steel Hardenability
- Induction Tempering

CHTE is located in Worcester, Mass., on WPI’s New England campus. The university was founded 150 years ago this year. For more information about CHTE, its research projects, and member services, visit wpi.edu/+chte, call 508.831.5592, or email Rick Sisson at sisson@wpi.edu, or Diran Apelian at dapelian@wpi.edu.

Surrounded by a traditionally cast metal part, Diran Apelian, director of WPI’s Metal Processing Institute, holds an intricate metal object fabricated layer by layer using additive manufacturing.

Other AM-related research is also underway in the areas of modeling, surface finishing, and new AM materials.

Sisson is developing databases and computational models to understand and predict the properties and performance of materials created using cold spray, a related AM process. The multiyear research program is funded by the U.S. Army Research Laboratory (ARL). ARL uses cold spray to repair magnesium gearboxes in helicopters and would like to use AM to produce entire replacement parts for its vehicles.

Associate professor of mechanical engineering Jianyu Liang and her research team are exploring electrochemical finishing techniques that can reduce the vulnerability of AM parts to fatigue and cracking.

Diran Apelian, director of WPI’s Metal Processing Institute, is collaborating with researchers at Lawrence Livermore National Laboratory in California (a CHTE member) to explore thixotropic metals that remain semisolid across a range of temperatures. By manipulating both temperature and shear, researchers hope to achieve the kind of precision required to additively manufacture complex metal components.

To learn more about AM research at WPI, visit http://wpiresearch.epubxp.com/i/502587-spr-2015.
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REDUCING GEAR SIZE FOR COMPACT TRANSMISSION DESIGN USING COMPUTER MODELING

Modeling shows that achieving required gear performance in a reduced gear size is possible by changing the steel grade and heat treatment parameters during the design stage.

Zhichao (Charlie) Li,* B. Lynn Ferguson,* FASM, and Andrew Freborg,* DANTE Solutions Inc., Cleveland

Gears are the most important components in transmission and actuator designs. In many cases, transmission or actuator design must be reduced to achieve weight or dimensional advantages without decreasing power density. One solution is to reduce gear size while keeping the same output torque capacity. In general, gears used in heavy load conditions are made of steel, and gear tooth residual surface stresses are critical to fatigue performance. Compressive residual stresses in the critical region of a gear improve its fatigue performance. However, many steel gears are not processed to obtain residual surface compression, or the benefit of residual compression is not considered in the gear and transmission design.

Steel gears are heat treated to increase hardness and strength for improved performance. Heat treatment introduces compressive residual stresses in the gear surface, which increases high-cycle fatigue performance[1–2]. Carburization and quench hardening generates compressive residual stresses in the gear surface due to delayed martensite transformation with volume expansion. These stresses reduce the magnitude of actual stresses generated in the critical location of gears under service load. Computer modeling is used to both troubleshoot and design heat treatment processes for steel parts[3–9]. In this article, virtual computer models using DANTE software are applied to help achieve gear size reduction by including steel grade hardenability and heat treatment in the design process.

GEAR GEOMETRY

A CAD model of an AISI 4340 alloy steel spur gear with 16 straight teeth selected for this study is shown in Fig. 1. Gear dimensions are 56 mm OD, 25 mm ID, 44 mm root diameter, and 50 mm thick. Quench hardening in oil is used to meet specified hardness and strength requirements.

The main concern for this gear is a failure at the gear root fillet during a high cycle bending fatigue test. Previous studies show that tangential stress at the root fillet under fatigue load is the main driver of fatigue crack initiation and propagation. Only one gear mid-plane cross section in the axial direction is used in this study.

High cycle bending fatigue performance is used as the main criterion to evaluate gear strength. To simplify the study, it is assumed that the driver and driven gears are the same size, and input and output torque (resistance) are the same. Figure 2a shows the setup of the gear pair under bending due to rotational torque load for the original gear size design, with a centerline distance of 103 mm. The driven gear is on the left, with a 3287 N·m resistance torque load applied in the direction as shown. A rotational displacement is applied to the gear on the right. Input torque is also 3287 N·m.

DANTE was used to model the oil quench process for the original 4340 steel gear and the magnitude of predicted...
residual stresses is negligible. It is assumed that residual stress from heat treatment of the original size gear is zero. To reduce gear size, a combination of carburization and oil quench is proposed to introduce compressive residual stresses to the gear surface for improved bending fatigue performance. AISI 8620 alloy carburizing grade was selected as the gear material, with a 25% reduction in the x-y plane while keeping the same axial dimension (Fig. 2b). Gear dimensions are 42 mm OD, 19 mm ID, 33 mm root diameter, and 50 mm thick. The volume or mass of the smaller gear is 56% that of the original gear, with the centerline distance between the gear pair reduced proportionally to 77 mm.

MODELING HEAT TREATMENT

The smaller gear is gas carburized, followed by oil quenching and low temperature tempering. The entire gear surface is carburized using process conditions of 925°C for 8 hours, with a carbon potential of 0.8%.

Figure 3a shows the predicted carbon-distribution (wt% C) contour. Predicted effective case depth (ECD) is 0.75 mm, assuming 0.4 wt% carbon as the threshold of ECD definition. After carburization, the gear is cooled to 875°C in the furnace, followed by oil quenching and tempering. Predicted martensite distribution is shown in Fig. 3b. The gear tooth is mainly martensite, the core about 20% martensite, and the remaining structure bainite. About 10% retained austenite is predicted on the carburized surface of the as-quenched gear prior to tempering.

Compressive residual stresses are generated in the gear surface after quenching. Predicted minimum principal stress is shown in Fig. 4a. Both bore and tooth surfaces are under compression due to the delayed martensitic transformation in the high carbon case. The root fillet has higher compressive stress compared with that at the tooth flank region, which is due to the stress concentration of the geometry effect during quenching.

The directions of minimum principal stresses vary at different locations of the gear. Minimum principal residual stress at the root fillet is in the tangential direction after quench hardening. Tangential stress also directly relates to fatigue crack initiation and propagation at the root fillet. A local cylindrical coordinate system is defined to plot the tangential stresses in the gear root fillet (Fig. 4b). The center of the cylindrical coordinate system matches the center of the gear fillet. The highest residual compression at the fillet is about 700 MPa, close to the center of the root. Using the local coordinate system, the stress contour close to the root fillet represents tangential stress, but stresses in this direction are meaningless for locations far away from the fillet.

MODELING GEAR STRESSES UNDER LOAD

Using the rotational bending setup shown in Fig. 2, stress evolution under a constant torque load of 3287 Nm is modeled using a linear elastic model. The highest tensile stress occurs at the root fillet during gear rotation. Without considering residual stresses from the heat treatment, snapshots with the highest stress magnitude are shown in Figs. 5a and 5b for both gear pair sizes. Reducing the gear size by 25% in the x-y plane generates 1075 MPa tensile stress at the root fillet compared with 600 MPa for the original size gear.

Compressive residual stresses introduced by heat treating significantly benefits the gear’s high-cycle bending fatigue strength. In this study, residual stresses from the hardening process shown in Fig. 4 are imported to the torsion load model. Under the same constant torque load of 3287 Nm, predicted maximum principal stress contour is shown in Fig. 6. To more clearly show the effect of residual stresses, the values are imported to the left (driven) gear only. The highest stress generated at the surface of the root fillet is slightly below 600 MPa, significantly lower than the value of 1075 MPa without considering residual stresses. From the contour plots shown in Fig. 6b, the highest stress is under the surface. The location under the surface could have a lower probability of crack initiation than that at the surface, even with higher tensile stress.

Fig. 3 — Predicted distributions of (a) carbon, and (b) martensite after hardening.

Fig. 4 — Distribution of residual stresses after carburization and oil quench: (a) minimum principal stress (MPa), and (b) tangential stress along the root fillet of gear using defined local cylindrical coordinate system.
Carburizing and oil quenching the 8620 steel gear introduces compressive residual stresses in the gear surface, which significantly reduces the magnitude of actual stresses at the root fillet under torsional load. Using the local cylindrical coordinate system described in Fig. 4b, predicted actual stresses in the tangential direction of the root fillet under the same torsional load of 3287 N·m are compared for the following three cases:

Case 1: Original gear size (4340 steel) without residual stresses from heat treatment
Case 2: Reduced gear size (8620 steel) with residual stresses from carburization and oil quench
Case 3: Reduced gear size (4340 steel) without residual stresses from heat treatment

For Case 1, the highest stress at the root fillet is about 625 MPa, located at point A (Fig. 7a). For Case 2, the highest stress is reduced to 600 MPa, and is located at point B, as shown in Fig. 7b, moving slightly from the root toward the gear tip, which is due to the nonuniform compressive residual stress at the root fillet. The combination of residual stresses and the applied stresses is shown in Fig. 7b. Based on the logic described above, the benefit of compressive residual stresses to fatigue performance is further improved by optimizing gear geometry and heat treatment, so the highest applied tensile stress location matches the highest compressive residual stress location after heat treatment.

During rotational bending, the history plot of tangential stresses at the most critical positions (points A and B in Fig. 7) of the root fillet are compared in Fig. 8 for the three cases. Either point A or B is used depending on which location has the highest actual stress under load. Peak stress is considered the main driver of bending fatigue failure. The comparison shows the significant effect of compressive surface residual stresses on bending fatigue performance.

CONCLUSIONS

The selection of gear material and heat treatment process is critical to bending fatigue performance. Carburizing and oil quenching gears made of a carburizing steel grade generates compressive residual stresses in the surface of the hardened case. These stresses benefit the high cycle bending fatigue performance of gears. The concept is validated by both modeling and previous experiments. In this study, the concept is further applied to reduce gear size without reducing its torque load capacity. A mass or volume reduction of 44% is compensated for by taking advantage of the compressive residual stresses generated by heat treatment. Material selection is also critical; clean material is preferred to reduce potential crack initiation sites under the hardened case, where residual tension exists to balance surface compression.

References


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Induction coils are considered the weakest link in an induction hardening system, so advanced designs and precise fabrication are paramount to ensure long life while producing high quality treated parts.

The terms hardening inductor, inductor, induction coil, and coil are all used interchangeably to describe the electrical component that provides the induction heating effect in an induction heating system. A hardening inductor is often simply called a coil, but its geometry does not always resemble the classic circular coil shape. Figure 1 shows a sample of numerous coil designs. A particular coil configuration depends on several factors such as workpiece geometry, temperature uniformity and required heat pattern, and production rate, among others. Alternating current flowing in the inductor generates a time-varying magnetic field that provides an electromagnetic link between the inductor and workpiece, resulting in contactless heating of either the entire workpiece, or selected areas.

Coils are considered the weakest link in an induction hardening system because they carry significant electrical power and operate in harsh environments exposed to high temperatures, water, and other coolants, while being subjected to mechanical movement and accidental part contact. Advanced coil designs and precise fabrication can ensure long life while producing high quality treated parts.

**MATERIAL SELECTION**

Copper and copper alloys are almost exclusively used to fabricate induction coils due to their reasonable cost, availability, and a unique combination of electrical, thermal, and mechanical properties. Proper selection of copper grade and purity for a coil is crucial to minimize the deleterious effects of factors that contribute to premature coil failure including stress-corrosion and stress-fatigue cracking, galvanic corrosion, copper erosion, pitting, water leaks, overheating, and work hardening. Cooling water pH also affects copper susceptibility to cracking.

Oxygen-free high-conductivity (OFHC) copper should be specified for most hardening inductors despite its higher cost. Besides superior electrical and thermal properties, OFHC copper dramatically reduces the risk of hydrogen embrittlement. The higher ductility of OFHC copper is also important, because coil turns are subjected to flexing and high electromagnetic forces. The higher cost of OFHC copper usually is offset by improved hardening inductor life.

*Member of ASM International and ASM Heat Treating Society

**FABRICATION TECHNIQUES**

Two traditional techniques used to fabricate hardening inductors are banding and brazing of square, rectangular, and round copper tubing. The ability to precisely and repeatably fabricate banded or brazed inductors of complex geometry has always been a legitimate concern, which requires an extensive and costly validation process after installing a new set of inductors.

Silver-base braze material is used to fill joint gaps in brazed copper tubing. The fact that electrical and thermal properties of pure silver are superior to those of copper has led some coil builders and practitioners to assume that the filler metal provides electrical contact between brazed components as good as with solid copper, which is not the case.

Porosity and the presence of oxides and other elements increase the electrical resistance of the brazed joint area compared with that of solid copper. As a result, excessive heat is generated in the copper joint area, unless the joint is located in a portion of the coil that does not carry electrical current. Excessive heat generation causes deterioration of brazed joints, shortening coil life.

A complex geometry inductor that contains numerous brazed joints, and 90° joints in particular, could experience impeded water flow in cooling coil turns, a problem more likely to occur in a coil fabricated with small-diameter tubing. This situation could require the use of booster pumps to provide sufficient water flow to cool the coil. However, this can be counterproductive as excessive water pressure adds to the electromagnetic forces and thermal stresses experienced by the copper coil, which could further weaken brazed joints, leading to cracking and water leaks. Also, brazed joints and the copper itself can weaken due to work hardening during coil service, becoming brittle and developing fatigue cracks. Eliminating or significantly reducing the number of brazed joints, particularly in current-carrying areas, is a key factor in fabricating long-lasting inductors.

**CNC MACHINING AND QUALITY ASSURANCE**

At Inductoheat, most high power-density hardening inductors are CNC machined from a solid copper bar regardless of complexity. This repeatable machining process produces rigid, durable inductors. CAD/CAM/CNC software programs are created that provide appropriate cutter-to-copper

spatial relationships, which produce inductors of the required shape and precision. Figure 2 shows a variety of finished and semifinished CNC-machined hardening inductors. In the past, most of these inductors were fabricated by brazing and banding coils. CNC machining is a superior method to achieve accurate, robust inductors for use in automotive, aerospace, defense and other industries where high process repeatability is critical.

Brazing is completely eliminated with some CNC-machined inductors, such as those used in Inductoheat’s nonrotational SHarP-C processes for hardening crankshafts and camshafts. Brazing is minimized in other applications, used only to encapsulate water-cooling channels.

Some inductors, especially those used in selective hardening, have very complex geometries. A computerized 3D metrology laser scanner is used to verify coil dimensional accuracy and alignment precision within about 25 microns (0.001 in.) after fabrication and assembly (Fig. 3).

CONVENTIONAL INDUCTORS

Steel shafts and shaft-like components are among parts that traditionally are induction hardened using scanning or single-shot heat treating. With the single-shot method, neither the shaft nor coil move relative to each other; the part typically rotates instead. The entire region to be hardened is heated at the same time.

A single-shot inductor consists of two legs and two crossover segments, also known as bridges or horseshoe half-loops (Fig. 4). Crossover segments encircle only half of the workpiece circumference, and induced eddy currents primarily flow along the length of the part. An exception is crossover segments where the flow of eddy current is half circumferential. Longitudinal leg sections are profiled by relieving selected regions of the copper to accommodate workpiece geometrical features, such as changes in diameter or irregularities. Section(s) of a single-shot inductor with narrower heating surfaces facing the shaft increase induced power density in desirable regions(s).

For a workpiece containing fillets, it is often necessary to increase heat intensity in the fillet region to heat the greater volume of metal. Also, the larger metal mass in the proximity of the heated fillet and behind the region to be hardened produces a substantial “cold sink” effect. This draws heat from the fillet due to thermal conduction, which must be compensated for by inducing additional heating energy in
the fillet area. The required energy surplus can be achieved by narrowing the current carrying face of the appropriate section of the single-shot inductor. For example, if the current carrying portion of the inductor heating face is reduced by 50%, there is a corresponding increase in current density, as well as the eddy current density induced within the respective shaft region. According to the Joule effect, doubling the induced eddy current density increases induced power density by a factor of four. Also, attaching a magnetic flux concentrator to certain areas of the hardening inductor (Fig. 4) further enhances localized heat intensity.

The effects of intensifying heat generation in selected areas of the shaft (i.e., excessive current densities in inductor sections combined with intense heat radiation from the workpiece surface) can cause localized copper overheating. This promotes water vaporization and the formation of a steam vapor barrier, which essentially functions as a thermal insulator inside the water-cooling pocket. Thus, copper cooling is severely restricted even when it appears that there is sufficient water-cooling flow and regardless of the use of high-performance pumps. To help prevent overheating, water-cooling pockets are placed as close as possible to the current carrying face of an inductor. However, coil overheating can still occur and cause accelerated deterioration of the copper surface, which speeds up the onset of inductor copper cracking (due to stress fatigue and stress corrosion, for example) and eventual premature coil failure. As a result, coil life is often shortened to 22,000-24,000 heat cycles (industry average). Therefore, the number of instances where coil current density is increased should be kept to a minimum.

Fig. 2 — Variety of finished and semifinished CNC-machined hardening induction coils.
Fig. 3 — A computerized 3D metrology laser scanner is used to evaluate fabricated coils to ensure geometrical accuracy and alignment, storing measurement data for inductor certification.

Conventionally fabricated single-shot inductors exhibit high process sensitivity, which has a negative effect on the repeatability of part heating and the quality of hardened components. High sensitivity is associated with an electromagnetic proximity effect. A change in positioning of the shaft inside the single-shot inductor due to bearing wear, incorrect part loading in the inductor, and other factors produces an immediate variation of heating intensity, particularly within the fillet region. This results in a local heat deficit and therefore reduced hardness depth.

**INDUCTOR BREAKTHROUGH**

Inductoheat recently developed a new inductor design (patent pending) that dramatically reduces localized coil current density in areas prone to overheating and cracking (Fig.5). The presence of a two-collar section reduces coil current by one half, which dramatically reduces localized heat generation in the copper and significantly extends coil life.

In addition, for a shaft positioned asymmetrically within the inductor, there is a reduced heating effect produced in one of the two half-collar sections that has an increased inductor-to-shaft gap. This is offset by an increased induced heating effect produced in the other half-collar section that has a reduced inductor-to-shaft gap. Consequently, process sensitivity associated with positioning the shaft within the inductor is reduced over that with a conventionally designed single-shot inductor.

Fig. 4 — A magnetic flux concentrator is attached to certain areas of the hardening inductor coil to enhance localized heat intensity.

Fig. 5 — Novel inductor design (patent pending) dramatically extends coil life in single-shot hardening of complex shaft-like components.
In one application of the new inductor, one of the world’s largest suppliers of automotive parts achieved a nine-fold increase in a single-shot coil life compared with that for conventional inductors. This is verified by the manufacturer’s tool-room tag showing that the inductor (which the customer named “magic coil”) was still considered in good shape after 225,000 heat cycles (Fig. 6). Other benefits include measurable improvement in process robustness, coil reliability, and maintainability.


Coil design details and benefits will be presented in a paper at Heat Treat 2015, taking place October 20-22 at Cobo Convention Center in Detroit.

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**Fig. 6** — Automotive component manufacturer’s tool-room tag indicates that Inductoheat’s newly designed inductor is still considered in good shape after 225,000 heat cycles, a nine-fold increase in single-shot coil life compared with that for conventionally designed inductors.
RULE #1. Choose the least expensive heat rejection technology

When choosing a cooling system consider your climate and the maximum operating temperature of your equipment for optimum efficiency. Lower fluid temperatures increase energy usage and operating costs.

<table>
<thead>
<tr>
<th>TYPE</th>
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RULE #2. Use hybrid systems to save energy

Combine different types of systems to achieve the best features of each with the greatest energy savings.

The "free cooler" shown at right eliminates the need for refrigeration compressors to run in a cold winter climate, saving energy and wear and tear on the chiller.

Another hybrid example is to "trim cool" an air cooled heat exchanger with an evaporative tower used in summer only. Substantial savings are realized in water, chemicals and electricity.

RULE #3. Get some expert advice. Make it pay to go green!

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ULTRAFAST BORIDING: A TRANSFORMATIONAL TECHNOLOGY

An ultrafast, efficient industrial-scale boriding process can drastically reduce costs, increase productivity, and improve the performance and reliability of a variety of machine parts. Component surfaces are converted into thick, hard boride layers in minutes, which dramatically increases resistance to degradation due to wear, abrasion, erosion, scuffing, and corrosion. By comparison, achieving such layer thicknesses using traditional pack boriding requires several hours, and surface hardness levels and other properties are lower than those produced using the new process.

The novel, environmentally friendly technology, developed at Argonne National Laboratory, Ill., enables treating thousands of industrial components in one batch, without creating solid or liquid waste and gaseous emissions. The key ingredient used during boriding is a natural borax mineral, which is safe to handle. Researchers say the new process is a transformational technology that can complement many current surface treatment processes, such as conventional boriding, carburizing, nitriding, carbonitriding, and physical and chemical vapor deposition (PVD and CVD).

PROCESS DEVELOPMENT

The ultrafast, large-scale boriding process is the result of a collaborative effort involving Argonne (lead partner), Bodycote, and Istanbul Technical University, stemming from a project funded by the U.S. Department of Energy-Advanced Manufacturing Office. The initial part of the project involved scale-up of a small proof-of-concept unit (1.75-in. diameter unit with 250-g electrolyte capacity) to 4- and 6-in. diameter intermediate units, and then to a pilot-scale unit with a 22-in. diameter crucible size featuring a capacity of 130 kg of electrolyte. This led to building a production-scale unit with a melt capacity of 4000 kg. The evolution of the large-scale boriding technology from inception to large-scale implementation is shown in Fig. 1.

The ultrafast method uses a battery-like design, where each electrochemical cell contains a positively charged cathode, negatively charged anode, and molten borax-based electrolyte. Bath temperature is roughly 1400°F. Parts are attached to the cathode, and when the unit is connected to a power source, ions flow from the anode to the cathode, depositing boron on the cathode and attached workpieces. Boron subsequently diffuses into the metal and reacts to convert near-surface regions into metal borides. The process is completed in minutes, producing a denser, more uniform coating, and requires 85% less energy than conventional boriding. Traditional pack-boriding, by comparison, involves baking parts in a complex mixture of powders at a temperature around 1800°F, often for 10 hours or longer.

Ferrous and nonferrous metals and alloys (e.g., titanium, tantalum, zirconium, tungsten, niobium, molybdenum, most nickel- and cobalt-base superalloys, and cobalt-chrome alloys), intermetallics, cemented carbides, and cermets (which are not possible to treat using conventional boriding methods) can be treated with the new process. Surface hardness is increased by factors of 3 to 10 (i.e., 15 to 45 GPa), depending on the specific alloy. For example, a 300-μm thick complex boride layer was formed on NiAl intermetallic material in 15 minutes,
TECHNICAL SPOTLIGHT

providing a surface with five times the hardness of the base material. Figure 2 shows examples of treated industrial parts. The microstructures and hardness of an ultrafast borided piston ring and pin are shown in Fig. 3. The superior properties produced by the process offer substantially longer product life, which indirectly reduces costs and energy consumption by minimizing repair and/or replacement of failed parts.

The electrochemical nature of the boriding process requires expertise in electrical engineering, electrochemistry, materials science, ceramics, furnace design, and various types of electrical power sources. Researchers from ANL include Ali Erdemir (ANL project lead), surface engineering expert Osman Eryilmaz, Gregory Krumdick (safety and quality control), and postdoctoral scientist Vivekanand Sista (boriding furnace instrumentation and operation). Experts from the Istanbul Technical University include Servet Timur, Guldem Kartal, and Ozgenur Kahvecioglu Feridun. Mario Ciampini from Bodycote served as liaison in many aspects related to the industrial-scale boriding system specification, benchmarking, field evaluation, and technology transfer issues.


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(a) - Treated engine parts and cross-sectional microstructures: (a) piston ring, (b) piston pin.

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**ATTRIBUTES**

<table>
<thead>
<tr>
<th>Flatter Parts</th>
<th>Avoid warped furniture</th>
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</thead>
<tbody>
<tr>
<td>Greater Throughput</td>
<td>Thinner plates, discs, rings, pucks &amp; racks</td>
</tr>
<tr>
<td>Complex Designs</td>
<td>Machine threads, holes &amp; contours</td>
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<tr>
<td>Quickly Heats &amp; Cools</td>
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<tr>
<td>Rapid Gas &amp; Liquid Quench Times</td>
<td>Thermal shock resistant &amp; low porosity</td>
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<td>Long Lasting Furniture</td>
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<tr>
<td>Heat Parts vs. Furniture</td>
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