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Editorial Opportunities for HTPro in 2014

The editorial focus for HTPro in 2014 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.

March  Energy Conservation/Combustion Control/ Heating
June    Process Control
September Surface Engineering
November Atmosphere/Vacuum Heat Treating

To contribute an article to one of these issues, please contact Frances Richards at frances.richards@asminternational.org. To advertise, please contact Erik Klingerman at erik.klingerman@asminternational.org.
New Supplement to Serve HTS Members

’t’s a bittersweet time for me, as I prepare to transition to my next role with the ASM Heat Treating Society (HTS). That new role is Past President, and while I’m happy to turn over the reins to Roger Jones of Solar Atmospheres, I’m also sad to see my term as President come to a close.

We’ve done some really great things in HTS over the past two years, and one of the most notable is the release of the first print issue of HTPro in Advanced Materials & Processes magazine, a copy of which you are holding in your hands right now. Let me share the back history on this. After many years, Heat Treating Progress ceased publication in 2009 after the economic downturn and decisions based on what was best for the Heat Treating Society. We entered into a relationship with Industrial Heating magazine to continue to provide our members with Heat Treating Society updates via the HTS Insider, and we enjoyed that partnership into 2013.

Our continued focus on generating quality technical content and the demand for print advertising with HTS, combined with an opportunity to join our efforts with ASM’s Advanced Materials & Processes magazine, resulted in the launch of the HTPro print publication, a quarterly supplement to AM&P, and the hard copy cousin of our HTPro eNewsletter. By putting ourselves in the ASM flagship print vehicle, we are expanding our audience within the ASM family and adding to the overall content growth strategy of ASM’s position as Everything Material.

As I come to the end of my term as HTS President, I want to thank all the committed men and women of our organization who devote their time and talents to the development of their professional society. You are the heart of HTS and your efforts are appreciated. To those of you who have not volunteered with HTS or ASM, I encourage you to consider doing so. Volunteering makes you a better professional; it broadens your understanding of our industry and enhances your professional and personal networks, improving you in ways you never dreamed of.

I look forward to seeing you at the HTS Conference and Exposition in Indianapolis.

Thomas E. Clements
President, Heat Treating Society

Where is Vision 2020 in 2013?

In 1999, the ASM Heat Treating Society Research & Development Committee created its Research & Development Plan, an implementation plan to achieve the high-priority research initiatives needed to accomplish Vision 2020 – a vision of what heat treating would look like in the year 2020. Vision 2020 describes the changes in both the structure of the industry and in heat treating processes required to reduce energy consumption, operating costs, and environmental impact by the year 2020.

The 1999 RD&D Plan identifies needs in three areas: Equipment and Hardware Materials, Processes and Heat Treated Materials, and Energy and Environment. In 2006, the RD&D Committee reviewed each area, identifying research completed or underway by industry, labs, and universities that directly or partially addressed various initiatives.

We are now operating in a different environment than we were at the last update of Vision 2020. A further update to show the progress in achieving objectives requires identifying completed and ongoing research and emerging technologies that address Vision 2020 goals. The Committee has taken on this task with a plan to prepare and publish an update on research progress, both to establish where we are now and to provide a framework for action to drive future research activities. The information will be included in updated initiatives and will also be shared in several overview articles to be published by the ASM Heat Treating Society in the newly launched HTPro quarterly magazine supplement. These overviews will help structure a framework for action to promote future research activities to achieve Vision 2020.

If you would like to contribute to this endeavor, you can provide information on completed and ongoing heat-treating related research at your organization. Please include the project name with a brief description of objective(s), results, benefits to heat treaters, and any supporting graphics. Send your material to Ed Kubel at ed.kubel@asminternational.org.

Heat Treating Society Announces Creation of the ASM HTS/Surface Combustion Emerging Leader Award

The ASM HTS/Surface Combustion Emerging Leader Award was established in 2013 to recognize an outstanding early- to midcareer heat treating professional whose accomplishments exhibit exceptional achievements in the heat treating industry. The award was created in recognition of Surface Combustion’s 100-year anniversary in 2015. The award acknowledges an individual who sets the “highest standards” for HTS participation and inspires others around him/her to dedicate themselves to the advancement and promotion of vacuum and atmosphere heat treating technologies. Rules for submitting nominations:

• Candidates must be submitted by an ASM International member.
• Nominations should clearly state the nominee’s impact on the industry and/or service and dedication to the future of the HTS. Three support letters should be included with the nomination.
• Nominees must be 40 years of age or younger, and employed full time in the heat treating industry for a minimum of five (5) years.

The award shall be presented to one (1) recipient every two (2) years at the General Membership Meeting at the HTS Conference and Exposition. Winner receives a plaque and $4000 cash award funded by Surface Combustion.

For rules and nomination form for the ASM HTS/Surface Combustion Emerging Leader Award, visit the Heat Treating Society Community Web site at http://hts.asminternational.org and click on Membership & Networking and HT Awards. For additional information or to submit a nomination, contact Sarina Pastoric at 440/338-5151, ext. 5513, or sarina.pastoric@asminternational.org.
HTS Names New Board Members for 2014

The HTS Awards and Nominating Committee named new board members including Steven Kowalski to serve as vice president for the 2013–2015 term; Stephen Mashl, James Oakes, and Jin Xia, to serve on the HTS Board for the 2013–2016 term; Aaron Birt to serve as student board member for the 2013–2014 term; and Jeff Sigelko to serve as young professional board member for the 2013–2014 term. Terms begin September 1, 2013. Leaving the board are Terrence Brown (past president), Subi Dinda (member), John Keough (member), Mike Schneider (member), Benjamin Bernard (young professional board member), and Charles Hartwig (student board member). Thomas Clements becomes past president, and Roger Jones becomes president on September 1, 2013.

Roger A. Jones is corporate president of Solar Atmospheres Inc., Souderton, Pa. After graduating from Hocking Technical College, he joined ABAR Corp. in 1975. In 1978, he joined Vacuum Furnace Systems Corp., founded by his father William R. Jones, FASM. In 1983, he helped found Solar Atmospheres Inc., serving as vice president, became president in 1993, and became corporate president in 2001. He has been a member of the Metal Treating Institute since 1983, serving on the Board of Trustees (1998–2004, and 2009–present), and as president (2004–2005). Roger has been a member of ASM Philadelphia Liberty Bell Chapter since 1983, and chapter president (1993–1994). He was chair of the ASM Heat Treating Society (HTS) Immediate Needs Committee and the HTS Education Committee, served on the Nominating Committee for two separate terms, and is a member of the HTS Technology & Programming Committee. He was elected to the HTS Board in 2005.

Steven G. Kowalski is president of Kowalski Heat Treating Co., Cleveland, assuming the position in 1997 for the second-generation family business. He earned his B.S. 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 Heat Treating Society 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 served on many non-profit 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. Steve has published several papers on furnace systems controls, high-pressure gas quenching, and government financing of business development.

Stephen J. Mashl is research professor at Michigan Technological University, Houghton, and heads Z-Met Inc., a materials consulting company. He also worked for Ames Laboratory (Iowa), the U.S. Naval Research Laboratory (Washington, D.C.), and Bodycote (Mass.). Stephen is currently chairman of the International HIP Committee and was program chair of HIP ’08. He is past president of the Advanced Particulate Materials Association, past member of the MPIF Board of Governors, and was technical co-chair of PowderMet 2009. He also served as Bodycote representative in the Center for Heat Treating Excellence (CHTE) at WPI. He authored more than 50 publications including the chapter on HIP of metal castings in the 2008 ASM Metals Handbook. Mashl is an active member of ASM International, the ASM Heat Treating Society, TMS, APMI, EPMA, and MPIF.

Jim Oakes is vice president of business development for Super Systems Inc. (SSI), Cincinnati. Since joining SSI in 2005, Jim 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, Jim worked at Oracle Corp., Redwood City, Calif., helping organizations leverage technology to become more competitive and improve processes with enterprise software solutions. Jim is on the board of the Metal Treating Institute and is a member of several committees focused on bringing value back to the members. He has been involved with ASM International for many years at the local chapter level, and contributed to the revised ASM Handbook on Heat Treating.

Dr. Jin Xia is Chief Materials Engineer for The Timken Co., Americas, Canton, Ohio. He earned his B. Eng. degree in materials science and metallurgical engineering from University of Chongqing, China, in 1982; his Ph.D. in materials science and metallurgical engineering from École Polytechnique de Montréal; and his MBA from University of Paris Dauphine, France, and Université du Québec à Montréal in 2003. Prior to joining Timken, he was an investigator at Analyse et Prévention de Défaillance Ltd. in Montreal (1989–1991); project manager and...
Hubbard Receives 2013 George Bodeen Heat Treating Achievement Award

Mr. John D. Hubbard, CEO (retired), Bodycote plc, headquartered in Macclesfield, Cheshire, UK, is the recipient of the 2013 George H. Bodeen Heat Treating Achievement Award.

Established in 1996, this award recognizes distinguished and significant contributions to the field of heat treating through leadership, management, or engineering development of substantial commercial impact. Hubbard is recognized “for a lifetime of devotion to and advancement of heat treating by transforming numerous small localized commercial heat treat providers into a network of knowledgeable and technologically strong heat treating facilities to meet the needs of the worldwide manufacturing community.”

Hubbard worked nights at Warner & Swasey while earning a B.S. degree in metallurgical engineering at Cleveland State University. After graduating in 1970, he was appointed metallurgical engineer and promoted to manager of heat treating departments for six facilities. He received his MBA from Cleveland State in 1973 and was a part-time adjunct professor for Business Ethics and Statistics at the university. He and a partner founded Furnace Services and Furnace Controls in Cleveland in 1973, and sold the companies in 1976. He joined Hinderliter Heat Treating Inc., North American Heat Treating Group in 1976 as general manager, and became president in 1983. Bodycote plc acquired the company in 1996 and Hubbard became president of Bodycote’s North American Thermal Processing Div. In 2002, he became CEO of Bodycote plc, growing the company from £479m (~$745m) and 5700 employees to £730m (~$1.1b) and 11,000 employees in more than 300 facilities in 32 countries when he retired.

Hubbard was on the Board of Trustees for the Metal Treating Institute (1983–1986 and 1994–2002), and was MTI president (2000–2001). He was a founding member of CHTE, was on the Heat Treating Society Board of Directors (1994–2000) and HTS president (2000–2001), and received the ASM Distinguished Life Member Award in 2005.

The award will be presented at the HTS General Membership Meeting on Tuesday, September 17, at the ASM Heat Treating Society Conference and Exposition in Indianapolis.
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The Center for Heat Treating Excellence Joins Industry with Academia to Address Critical Research Needs

While research and discovery are necessary for innovation, not all segments of the industry are able to keep pace. To bridge this gap, industry leaders working together with university researchers at Worcester Polytechnic Institute’s (WPI) Center for Heat Treating Excellence (CHTE) are solving business challenges and improving manufacturing processes. Projects are aimed at reducing cycle times, increasing furnace efficiency, enhancing heat treating process control, improving surface treating processes, and increasing energy savings, efficiency, and conservation in heat treating operations.

Since its launch in 2000, CHTE continues to provide a forum for the heat treating industry to pool its resources and engage in collaborative and innovative research to advance the industry. Members include leaders from both industry and academia, and by joining forces, CHTE created an organization of unsurpassed technical expertise and results-oriented networking.

Collaborative Research
CHTE industry members collaborate with WPI faculty and students on research projects targeted at solving real-world problems by selecting projects that meet their most demanding business needs. Projects focus on high-priority issues including: Surface engineering (carburizing, nitriding, and carbonitriding); Improvements in furnace fixtures and alloy service life; Cycle time reduction; Energy efficiency and savings; Nondestructive examination; Gas quenching; Induction tempering; Quality control; Control of distortion and residual stress; and Solutionizing and aging of aluminum alloys.

A few of the Center’s recent projects include: Nondestructive Testing for Surface Hardness and Case Depth
The heat treating industry requires accurate, rapid, and nondestructive techniques to measure the surface hardness and case depth on carburized steels for process verification and control. The objective of the present study is to identify, develop, and verify nondestructive techniques that overcome the limitations of current measurement methods.

Carbonitriding – Fundamentals, Modeling, and Process Optimization
CHTE collaborators are working to model the process and determine boundary conditions for carbon and nitrogen absorption, and diffusion coefficients of carbon and nitrogen in steel during the carburitriding process.

Nitriding – Fundamentals, Modeling, and Process Optimization
Gas nitriding often suffers from poor performance reliability, limiting its application. To help achieve reliable performance, CHTE researchers are building an effective model to simulate gas nitriding of steels, based on the fundamental understanding of thermodynamics and kinetics.

Gas and Vacuum Carburizing
To save businesses time and money, CHTE researchers are optimizing industrial carburizing process parameters by developing effective gas and vacuum carburizing models through a simulation program called CarbTool, which calculates the carbon concentration profile during the processes.

Induction Tempering
CHTE collaborators are developing a fundamental understanding of the induction tempering process, including the effects of induction process parameters of power (kW) and frequency (kHz) on the microstructure and properties of the induction tempered part. A comparison of the microstructures, residual stress distribution, and mechanical properties (hardness, impact toughness, and torsional properties) of induction tempered steels with furnace tempered steels is also underway.

High Pressure Gas Quenching
CHTE is actively working to develop a standard method (procedure and device) for evaluating material Hardenability for gas quenching, which involves slower cooling rates than are encountered in oil and water quenching. Researchers are also developing a standard method to characterize the cooling in a given gas quench system.

Heat Treating Energy Use and Reduction
Energy costs are a major concern for the heat treating industry, so collaborators use the U.S. Department of Energy’s PHAST software to identify energy losses in a variety of furnaces and recommend methods for conservation.

Results-Oriented Networking
CHTE members include leaders from commercial and captive heat treaters, suppliers, and manufacturers. Membership offers the opportunity to network and share ideas and knowladge on common problems and issues. Industry members include: Air Liquide, Air Products, ALD, ASM International, Bluewater, Caterpillar, Chrysler, Cummins, Deformation Control Technology, GKN Sinter Metals, Harley-Davidson, John Deere, Lawrence Livermore National Lab, Sikorsky, Praxair, Sousa Corp., Spirol, Surface Combustion, Thermatool, Thermo-Calc Software, Timken Co., and others.

Unsurpassed Technical Knowledge and Expertise
CHTE is supported by WPI – one of the top engineering universities in the world. The CHTE team consists of research experts in surface treating, process modeling, heat and mass transfer, solidification processing, aluminum alloy development, computer-aided fixture design, and degradation phenomena.

"CHTE makes it easy to tap into a pipeline of invaluable knowledge and a far-reaching network of excellent people with countless years of heat treating experience." Alexander Brune, Sikorsky Aircraft

For more information about CHTE and its member services, visit www.wpi.edu/+chte.
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**2013 EXHIBITOR SHOWCASE**

The exhibit hall at the 27th ASM Heat Treating Society Conference and Exposition in Indianapolis will be packed with quality company displays.

A few key exhibitors are highlighted here. Visit them on September 17 (9:00 a.m. – 6:00 p.m.) and 18 (9 a.m. – 5:00 p.m.) at the Indiana Convention Center. Be sure to attend the Networking Reception 5:00 p.m. – 6:00 p.m. on Tuesday night.

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Offering thermal processing solutions to meet the increasing demand for flexible, scalable heat treatment systems with consistent, repeatable metallurgical results. Our featured UBQ (Universal Batch Quench) system is capable of running a variety of metallurgical processes; whether a single unit or as a complete, fully-automated cell integrated with companion equipment. With its compact, modular design, additional cells can be added for maximum production flexibility.

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**Booth 1817**

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**Dry Coolers Inc.**

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**BeaverMatic Inc.**

Jack Beavers began a determined journey toward furnace innovation with simplified yet sophisticated equipment designs 50 years ago. From our past successes and solid installation base, BeaverMatic remains steadfastly focused on its core competency to build simplified yet dependable performance-proven equipment. Today, BeaverMatic is a family-owned manufacturer of custom, standard, batch and continuous atmosphere heat-treating equipment. Best known for the Internal Quench Furnace with Beaver Ram transfer system, BeaverMatic’s product line includes temper furnaces, washers, endothermic gas generators, box furnaces, pit furnaces, continuous pushers, carbottom furnaces, and tip up furnaces. Come visit us in booth 2016 where we will feature the various Internal Quench furnace configurations that we have available. [www.beavermatic.com](http://www.beavermatic.com)

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Inductoheat Inc.

Inductoheat Inc. will again be attending the ASM Heat Treating Society Conference and Exposition September 16th through 18th. We encourage everyone to take advantage of this opportunity to view our latest advancements in induction heating technology. Inductoheat Inc. will be located at booth #1701 and our Team is looking forward to walking you through our exhibit and introducing you to our new IFP (Independent Frequency & Power) power supply.

For more information about our induction heating, heat treating and forging equipment, please visit our website, www.Inductoheat.com.

Booth 1701

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United Process Controls provides process control, flow control, and automation solutions to furnace OEMs and customers with thermal processing equipment and operations. Products range from probes, analyzers, flow meters, programmable controllers, generator and gas mixing control systems, SCADA to complete turnkey systems.

The company is comprised of four brands - Furnace Control Corp, Marathon Monitors, Process-Electronic, and Waukee Engineering. www.unitedprocesscontrols.com

Booth 1823

Induction Tooling Inc.

Induction Tooling Inc. has received ISO/IEC 17025 Accreditation for Mechanical Testing. Since our core business is the design, fabrication and repair of heat treat inductors and associated tooling, it made sense to integrate our induction and metallurgical laboratories. The induction laboratory is a valuable extension of our services, allowing us the ability to not only design and fabricate high quality inductors, but also characterize them on-site. The Metallurgical Laboratory will record process parameters for production and formally validate the results in a format that can be submitted directly to the end customer. We recognize a significant reduction in the time required to get inductors from design and into production. Additionally, ITI will provide testing services to the general heat treating industry. www.inductiontooling.com

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ICME TOOLS CAN HELP CONTROL GEAR DISTORTION FROM HEAT TREATING

INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING TOOLS ENABLE ACCURATE SIMULATION OF GEAR HEAT TREATMENT TO PREDICT PHASE TRANSFORMATION KINETICS AND DISTORTION.

Junsheng Wang, Xuming Su, and Mei Li
Ronald Lucas and William Dowling*

Most gears used in industrial applications are carburized and quenched to meet surface and core hardness and overall fatigue strength requirements. Low pressure vacuum carburizing (LPC) combined with high pressure gas quenching (HPGQ) offers the opportunity to minimize environmental impact, eliminate oxidation and surface decarburization, accurately control case depth and core hardness, and produce consistent microstructure, and thus, fatigue performance from batch to batch. LPC/HPGQ has the potential to minimize distortion by controlling such parameters as gas flow velocity, operating pressure, chamber geometry, and fixture materials. A time-efficient, cost-effective way to optimize those parameters is to integrate various computational tools such as computational fluid dynamics (CFD), finite element analysis (FEA), and microstructure modeling to perform numerical tests for specific type of gears. This article discusses the development of an integrated computational materials engineering (ICME) tool and its practical application in product development.

Manufacturing challenges
Increasing demand for vehicle fuel efficiency has led to weight reduction of transmission components, and transmission gears of thinner cross section are more sensitive to distortion during manufacture[1-2]. Transmission gears have very tight dimensional tolerances to meet durability, as well as noise, vibration, and harshness (NVH) requirements. This creates processing challenges from machining through heat treating. Along with the effects of residual stresses from machining, distortion is caused by nonuniform plastic deformation due to thermal and phase-transformation stresses during heat treatment. Parts that do not meet quality control specifications may require additional grinding and other corrective measures to meet dimensional tolerances, which significantly increases costs.

Low pressure carburizing combined with high pressure gas quenching produces less distortion compared with other heat treating methods[3-4]. It consists of vacuum carburization at an austenitizing temperature of ~930°C followed by high pressure nitrogen gas quenching at 1–20 bar (Fig. 1a). Acetylene is supplied at low pressure in several boost intervals, because its decomposition is catalyzed by iron atoms at the gear surface, providing high carbon potentials for diffusion into the austenitic structure[5]. After achieving the desired 0.3–1.0 mm carburized case depth, the workload is transported into the quenching chamber where controlled cooling using high pressure, turbulent nitrogen gas flow produces the desired microstructure[6]. Surface and core hardness, as well as properties such as fatigue strength, wear resistance, and pitting corrosion resistance are determined by the microstructural constituents resulting from different cooling rates and carbon profile[6].

For example, a straight quench at constant pressure and velocity leads to a large temperature difference between the gear surface and core, introducing nonuniform thermal and martensite-transformation stresses, which can cause distortion as shown in Fig. 1b. Stop quench, dynamic quenching, and reversing quenching are recent developments[1-5] used to control cooling rate (and thus phase transformation) in three steps: (1) high quench severity prior to martensite phase transformation to

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*Member of ASM International

Fig. 1 — (a) LPC and HPGQ heat treating process and schematics of (b) straight quench and (c) step quench.
avoid pearlite formation, (2) temperature equalization in each part, and (3) fast cooling to generate martensite for surface and core hardening (Fig. 1c).

The prediction of heat transfer in combination with the phase-transformation process during HPGQ has become increasingly important as more attention is paid to optimizing the quenching process to minimize distortion\textsuperscript{8-10}. The need for CAE tools that can predict the conjugate heat transfer during high pressure gas quenching and couple it with phase transformation distortion analysis led to the development of ICME-GearHT.

Computational tool development
The ICME-GearHT tool enables accurate simulation of the transmission gear heat-treatment process, predicts phase transformation kinetics and distortion, and provides cost-effective, time-efficient evaluation of new equipment designs. These will ensure high quality product launch and help achieve a “first-time-through” manufacturing vision (Fig. 2). This was accomplished by gaining a clear understanding of the fundamentals of carburizing, conjugate heat transfer, phase transformation, and micromechanics during the gear heat treatment process; and integration with the most advanced models in different disciplines\textsuperscript{8-10} and related leading industrial experimental validations.

ICME-GearHT analysis is broken down into four parts: carburization, CFD, phase transformation, and mechanical analysis. Figure 2 shows the data requirements and how the analyses are coupled. Each analysis starts from diffusion-based carburization at high temperature using carbon potentials and diffusivities measured from experiments. The Abaqus (Dassault Systèmes) FEA model calculates the kinetic process of carbon diffusing into austenitic interstitial sites, which expands the lattice, and introduces a carbon gradient into the gear. The resulting nodal carbon concentrations serve as input to the subsequent high pressure-gas quench analysis. Transient heat transfer is calculated using the Fluent (Ansys Inc.) CFD model, in which the latent heat of phase transformation is implemented as a subroutine. Carbon concentration (from FEA) and temperature values (from CFD) are fed into the DANTE (Deformation Control Technology Inc.) microstructure model. Finally, the coupled Abaqus CAE and DANTE database performs structural analysis for mechanical properties of each phase. As shown experimentally by previous authors\textsuperscript{1-4}, surface carbon concentration has little effect on gear distortion. Temperature and phase evolution at different locations/orientations control thermally and transformation-induced plasticity.

Model validation
The following example case illustrates thermal model validation and compares predicted and experimental results. Because different cooling rates result in different volume fractions of martensite, nonuniform cooling rate on a single gear results in nonuniform distribution of martensite in the gear (Fig. 2). Martensite transformation causes a 2–5% volume increase\textsuperscript{11} depending on the composition and releases about 3.1 x 10\textsuperscript{9} J/m\textsuperscript{3} latent heat\textsuperscript{12}, which complicates the temperature profile of each gear. Therefore, it is important to include transformation kinetics in modeling the transient temperature history of gears during quenching\textsuperscript{13}. However, commercial CFD codes are intrinsically unable to accurately predict the thermal history of the gear quenching process due to the lack of a phase-transformation model. We implemented a subroutine in the commercial Fluent CFD code to take the latent heat effect due to phase transformation into account.

Model validation is accomplished using experimentally measured temperature data (Fig. 3 I-a) at 40% and 100% fan speeds. Figure 3 I-b shows that higher cooling velocity results in higher heat-transfer coefficient. The predicted thermal profile captures the effect of latent heat release, agreeing well with experiments for different gear orientations (Fig. 3 I-c). Temperature uniformity during HPGQ is critical for improving process performance to minimize distortion and maximize gear service life. Therefore, the ICME-GearHT model was used to evaluate properties of furnace-fixture materials, chamber configurations, and parts loading in the furnace.

Experimental validations
New kinetic parameters were developed for 5130 alloy steel, which is widely used for transmission gears. Kinetic parameters in the phase transformation models were determined using an optimization approach that matches model predictions with experimental measurements. The parameters were implemented into the DANTE materials database, allowing accurate prediction of phase transformation and seamless integration with the micromechanical model for calculating both thermal and transformation plasticity during the gear quenching process.

Distortion analysis using ICME-GearHT is validated by mapping the distortion at various locations of the load and at three different quenching conditions including step quench, 40% fan speed, and 100% fan speed. The experimental setup is shown in Fig. 3 II-a. Experimentally measured distortion at three different conditions (Fig. 3 II-b) agrees well with previous studies\textsuperscript{7}. Step quenching produces less distortion and better product quality. Distortion calculations determined using the ICME-GearHT approach are compared with experimental results to provide efficient, effective solutions for process design and optimization. Figure 3 II-c shows predicted gear
circularity, replicating the influence of gear location on distortion and matching experimental measurements in locations 8 and 9. Results show the model can be used to optimize production processes and identify the best heat-treatment recipe for minimized distortion.

Recent experimental studies by others[1-4] have shown that use of carbon-fiber composite (CFC) fixtures reduces distortion by 25%, and by 50% by combining CFC fixtures with a step quench. Computations were performed using both alloy and CFC fixtures to quantitatively evaluate the benefits of new fixture materials. CFC fixtures significantly improve temperature uniformity within the load and within individual gears with the same load volume as in a steel basket. An improvement of 20–25% in temperature uniformity is possible using CFC fixtures. Evaluation of modifications to the quenching system using ICME-GearHT shows that a proposed new cooling fan and stator design along with velocity filtering improves temper-
ature uniformity prior to martensite transformation by more than 20%.

Summary

The ICME-GearHT model incorporating latent heat release due to phase transformation was validated using experimental data. The entire workload is a complex thermal body subjected to large temperature variations during quenching. ICME-GearHT captures those variations. It was used to investigate and validate a new gas quenching process, propose cost-effective, time-efficient recommendations for new transmission-product development, and accelerate new process development. It was also used to evaluate the benefits of using different heat treating furnace-fixure materials and different quenching furnace stator and fan designs to improve temperature distribution uniformity for reduced distortion.

Fundamental and experimental methods developed using ICME-GearHT can be extended to any high pressure gas quenching process such as sun-gear and pinion-gear heat treatments. It can be extended to any case-hardening process such as induction hardening, oil quenching, and molten salt quenching.

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LOW-DISTORTION, HIGH-QUALITY INDUCTION HARDENING OF CRANKSHAFTS AND CAMSHAFTS

REDUCING THE AMOUNT OF HEAT GENERATED WITHIN A PART AND PROVIDING UNIFORM HEATING WITHOUT APPLYING FORCE GO A LONG WAY IN CONTROLLING PART DISTORTION DURING INDUCTION HARDENING.

Gary Doyon*, Valery Rudnev, FASM*, and John Maher*

Crankshafts, typically made of plain- and low-alloy medium carbon steels (e.g., SAE 1039M, 1042, 1538M), consist of a series of crankpins (also called pin journals or pins) and main journals (mains) interconnected by crank counterweights. Journal diameters on crankshafts used in automobiles, tractors, and other vehicles range from 35 to 60 mm. Several induction hardening methods are used to surface harden crankshaft features such as pins, mains, and oil seals, providing hardness in the range of 52 to 56 HRC after hardening and tempering. Hardened case depth typically ranges from 0.75 to 2 mm after grinding.

Depending on crankshaft design and process requirements, crankshaft journals are induction hardened using either band hardening or band-and-fillet hardening (often simply referred to as fillet hardening). Band hardening is used to harden only the bearing surfaces. The hardness pattern typically ends about 0.5 to 1.5 mm from the journal fillet. Figure 1 shows induction band hardening patterns on etched crankshaft journals for a V-8 automobile engine. Roll hardening is applied after induction band hardening to induce useful compressive residual stresses in the fillet area. Band hardening results in smaller distortion, which reduces the amount of grinding stock required.

Induction hardening using the rotational process

From the 1960s to 2000, most induction crankshaft-hardening machines used non-encircling U-shaped inductors, which physically ride on the journal using carbide guides (also called locators or spacers), while the crankshaft rotates in centers during heating and quenching. The complex crankshaft geometry lacks symmetry, in particular around pin journals (pin axes are offset radially from the main axis). Therefore, pins orbit the main axis during rotation. The circular orbital motion of a massive induction heating and quenching system (often exceeding 900 kg including a set of water-cooled inductors, buswork, cables, etc.) must be precisely maintained using a special control tracking system. Such systems provide time-dependent power modulation for each heated journal during its rotation, depending on specific counterweight geometry and the presence of oil holes.

U-shaped inductors inherently produce a nonsymmetrical heating pattern at any given time, because heat is only applied to less than half of the crankshaft journal. The rest of the pin/main undergoes a soaking-cooling cycle. Nonsymmetrical heating requires relatively prolonged heating times (8 to 20 s), which, in turn, heats an appreciable mass of metal, resulting in greater shape distortion and causing nonuniform hardness profiles around the perimeter. In addition, U-shaped inductors are fabricated either by banding or brazing copper in the shape of a figure eight containing multiple bands/joints (Fig. 2, top). Both coil fabrication methods raise concerns about the...

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precision and repeatability of complex coil geometry construction, which requires extensive process validation after a new set of inductors is installed.

Induction hardening using a nonrotational process

The development of nonrotational induction hardening technology was an advancement in the induction hardening of crankshafts. The patented SHarP-C (Stationary Hardening Process for Crankshafts) technology was introduced in early 2000, and continual improvements established it as a proven process that eliminates the need to rotate the crankshaft during heating and quenching cycles. Millions of crankshafts have been heat treated using SHarP-C since its introduction.

The inductor for the nonrotational hardening process consists of two sections (Fig. 2, bottom) machined from a copper block: a top (passive) inductor and bottom (active) inductor. The bottom inductor is connected to a medium-frequency power supply, and the top inductor represents (electrically) a short circuit (closed loop). The bottom coil is stationary, while the top coil can be opened and closed. Each inductor has two semi-circular areas to locate journals to be heat treated, while the top inductor is in the "open" position.

A robot loads the crankshaft into the heating position, the top coil pivots into a "closed" position, and power is applied to the bottom coil. Electrical current flows in the bottom coil, and with a lamination pack that serves as a magnetic flux coupler, both top and bottom coils are tightly electromagnetically coupled. Current flowing in the bottom coil instantly induces eddy currents that begin to flow in the top coil. According to Faraday’s law of electromagnetic induction, the induced currents are oriented in a direction opposite that of the source current, similar to a transformer effect.

The heated crankshaft journal “sees” the nonrotational inductor as a fully encircling, highly electrically efficient induction coil. Crankshaft journals are heat treated sequentially resting on V-blocks. No axial force is applied.

SHarP-C technology dramatically reduces distortion and offers simple operation, equipment reliability and maintainability, and a substantial reduction in life cycle cost.

Inductors are CNC machined from a solid copper block; eliminating brazed and banded components makes them robust, rigid, and repeatable. This reduces the possibility of inductor distortion during fabrication, thereby eliminating the associated hardness pattern drift.

Shape and size distortion and total indicated runout (TIR) are very important parameters of the crankshaft hardening process. TIR directly affects the amount of metal required to be ground off after hardening. One of the most important factors that impacts crankshaft distortion is the amount of heat generated within the crankshaft body. The greater the mass of metal heated, the greater the thermal expansion, which, in turn, causes greater distortion of components with complex, nonsymmetrical geometry.

Nonrotational technology also shortens heating time by an average of 3 to 4 fold compared with that for the rotational process, which reduces the mass of metal heated. Journal cores remain relatively cold during the entire heating cycle, serving as a shape stabilizer and practically eliminating shape distortion. A smaller heat-affected zone (HAZ) also reduces thermal expansion.

Rotational hardening applies appreciable axial force on the crankshaft to rotate it during hardening, which results in residual stress in the crank. By comparison, the SHarP-C process places no axial forces on the crankshaft as it rests in V-blocks during hardening, thereby minimizing stresses in the shaft. Lateral growth is minimized and distortion and TIR typically does not exceed 25 microns.

Hardening camshafts

Camshafts consist of several sets of cam lobes and bearings. Cam lobe shape varies depending on engine design. Depending on camshaft geometry and production requirements, shafts may be induction hardened using
Scan or static (single shot) heating of one or more lobes, which can be rotated or motionless during heat treating.

Scan inductors offer the greatest flexibility by enabling lobes of various lengths to be heat treated using minimum power, because only a portion of the lobe is heated. Low production rates, due to single-lobe processing, are the main limitation of using a scanning technique to surface harden automotive camshafts. Trying to produce the required range of “minimum-maximum” hardness case depths is also a challenge. In addition, heating lobes that have an appreciably different ratio of cam-nose diameter-to-base-circle diameter is difficult unless lobes are stationary during processing and properly oriented with respect to the profiled inductor. Scan hardening is also difficult when lobes are in close proximity to each other (i.e., triple-lobe cams).

In contrast to scan hardening, static, or single-shot, heating of multiple lobes is commonly used when surface hardening small and medium size automotive camshafts with lobes of the same size and shape and having the same or very similar axial gaps between them. In this scenario, deeper case depth typically occurs in the nose compared with the base circle (the heel). The cam-lobe nose has a closer electromagnetic coupling with the inside diameter of the copper coil. This is one of the main causes of deeper case depth in the lobe nose area compared with its base circle region, leading to camshaft distortion.

Short heating times, the ability to develop a uniform austenitized layer, and processing camshafts horizontally without applying any pressure during heat treating are factors that contribute to a reduction in camshaft distortion. Low distortion can potentially eliminate the camshaft straightening operation and reduce the allowance for grinding stock. Figure 4 illustrates true contour hardening of camshaft lobes using inductors that provide uniform coil-to-lobe gaps and short heat times.

The nonrotational SHarP-C technology developed for crankshafts can easily be applied for low-distortion camshaft hardening, providing true contour-hardening profiles, dramatically minimizing distortion, and potentially eliminating the need for post-hardening camshaft straightening. HTTPRO

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Changes in thermal distribution throughout an induction hardening process create complicated phase transformations and stress evolutions in the component. Both residual stresses and mechanical properties of the hardened pattern have a significant impact on service performance of the heat treated parts. Induction hardening of steel components is a highly nonlinear transient process, and understanding the changes in stress state due to hardening is not intuitive. Electromagnetic and thermal-stress analyses of induction hardening have matured with the development of FEA modeling capability, and they are applied to understand and solve industrial problems. FEA is used to predict mechanical properties and residual stresses, which are further used to analyze the mode and location of fatigue failures. Component geometry and process can also be optimized to reduce part weight, trim manufacturing costs, and improve performance.

Induction hardening of steel components is a common processing method due to fast heating times, high efficiency, and ability to heat locally. However, predicting final properties of a hardened component adds another layer of complexity. Temperature and structure must be considered, as well as electromagnetism. When hardening steel, magnetic properties change throughout the process, affecting thermal distribution and structure. Coupling these phenomena to achieve end properties after treatment is a state-of-the-art technology. In a simple case, stress and distortion modeling of ID and OD hardening of a tubular product was investigated. To study a component common in industry with a more complex geometry and subjected to external stresses in service, a full-floating truck axle with dimensions typical to those manufactured by Dana Corp. was selected. Using an axle (a common automotive component) enables comparing simulation results to desired axle properties. Results are compared to typical performance criteria for the selected axle. The goal is to produce results representative of actual part performance.

**Part geometry and model for thermal/stress analysis**

Axles must be surface hardened for durability to prevent failure in service. Hardening is commonly performed using induction scanning. Induced stresses and distortion are affected by the method in which the induction scan process is performed. Bowing distortion and change in length are the main con-
cerns during induction hardening of truck axles with shafts more than 1 m long. Bowing distortion can be minimized by proper inductor design, process control, and structural support mechanisms. Excessive heating of the shaft core is the main contributor to distortion, which can be evaluated by simulation. Change in length is affected by both shaft heating and cooling rates, a nonlinear process. The shaft studied here is a full-float truck axle made of AISI 1541 from Dana Corp. A simplified CAD model is shown in Fig. 1. Shaft dimensions: 34.93 mm diameter, 1008 mm long, 9.52 mm fillet radius between flange and shaft, flange diameter and thickness are 16.5 mm and 104.5 mm, respectively. The spline has 35 teeth; a single tooth sector with cyclic symmetric boundary condition is modeled in this study.

Heat treating process
During the scanning induction hardening process, the axle is positioned vertically with the flange on the bottom of the fixture. The distance between inductor and spray is 25.4 mm. The process starts with static heating of the flange/fillet for 9 s followed by scanning with a 15 mm/s inductor travel speed. Scan speed is decreased to 8 mm/s after 1.5 s and remains at this speed. Power is turned off after an additional 119.65 s, just before the shaft end is austenitized. Spraying continues after power is turned off to complete transformation of the austenitized section of the shaft to martensite.

Inductor design and power density modeling
It is critical not only to meet the hardened depth requirement, but also to prevent excessive heating in regions such as the flange, core, and shaft end. Too much heat in these regions increases the possibility of cracking, and can lead to excessive distortion. The minimum case depth requirement for this axle shaft is 5.4 mm, and case depth is defined by a hardness of 40 HRC.

Inductor design must prevent cracking and excessive distortion. A machined two-turn coil with a Fluxtrol A magnetic flux concentrator was configured using Flux2D FEA software. Figure 2a shows a finite element meshing used to model the axle by Flux2D, with a schematic temperature distribution focusing on flange and fillet regions. The axle material is magnetic, and power density distribution varies greatly as the temperature exceeds the Curie point. Inductor frequency is 10 kHz, the common operating frequency of Dana’s induction machines for this class of parts. Different finite element meshes are used for Flux2D and DANTE models due to different physics and accuracy requirements.

A 3D finite element mesh of a single spline tooth is used in the DANTE software for thermal, phase-transformation, and stress analyses. Fine surface elements are used to effectively model the thermal and stress gradients near the surface. Power densities in the axle predicted by Flux2D are imported and mapped into DANTE. The mapping process is implemented at 0.5-s intervals, and the power between two power snapshots is linearly interpolated. Figure 2b shows temperature distributions pre-
dicted by DANTE at various times of the process. Temperatures predicted by Flux2D and DANTE agree well.

Stress and phase-transformation modeling

The first step of the induction hardening process is a 9 s dwell allowing heat to build in the flange/fillet region; the inductor is stationary with no spray quenching. Following the dwell, the inductor moves up at a speed of 15 mm/s for 1.5 s, after which the speed drops to 8 mm/s and spray quench starts and continues for the duration of the process. Power and temperature distributions are stable during scanning over most of the shaft length. Figure 3 shows temperature, austenite, hoop stress, and radial and axial displacements at 16.5 s after the process begins, using a 25 kW/m² C heat transfer coefficient as a boundary condition. The austenite layer transforms to martensite during spray quenching. Figure 3c shows in-process hoop stress distribution, which shows the effect of thermal gradient and phase transformation. The displacement in Fig. 3 is magnified 10 times, so shape change can be clearly viewed.

Cooling rate has a significant effect on residual stresses in the part. Figure 4 (left) shows axial residual stresses predicted using the three cooling rates with heat transfer coefficients of 5, 12, and 25 kW/m² C. A faster cooling rate generates higher residual compression on the surface. To balance the surface stress, the core also shows higher tension. The highest tensile stress in the axial direction is located at the centerline of the shaft above the flange, which is mainly due to the extra heat required to harden the fillet. Predicted axial displacements for the three cases are shown in Fig. 4 (right). Axial growth is predicted for all cases. The same legend is used for the three contours in Fig. 4 (right), so the color difference represents the magnitude of axial distortion. Axial displacement in the shaft is not linearly distributed along the axis, because it is not stabilized during early scanning of the shaft. Axial displacement from the center to the surface of the shaft varies. Comparing the three cases modeled shows that a higher cooling rate leads to higher axial growth.

Fig. 3 — From left to right: temperature, austenite phase, hoop stress, radial displacement, and axial displacement distributions at the end of 16.5 s in the induction heating process: Heat transfer coefficient = 25 kW/m² C.

Fig. 4 — Axial residual stresses (left) and axial distortions predicted from three quenching rate models (right).

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Plasma nitriding and plasma nitrocarburizing are used to improve wear and corrosion resistance, as well as fatigue strength of steel components. Compared with conventional gas and salt-bath nitriding methods, plasma nitriding offers advantages of lower energy and gas consumption and the ability to be integrated into in-line manufacturing processes. The process is environmentally friendly as well. Additionally, partial nitriding is possible by masking areas where nitriding is not required; surface enrichment with nitrogen and carbon occurs only at areas exposed to the plasma glow discharge. Glow-seam thickness is highly dependent on process parameters, especially gas pressure. Adjusting working pressure improves the plasma seam for true shape coverage of components with a complex geometry.

Limitations of plasma nitriding stem from applying the plasma discharge energy directly onto the surface of parts to be treated, resulting in a nonhomogeneous temperature distribution through the workload, especially for components with different surface-to-volume ratios. Therefore, only parts with similar geometries can be treated together in the same batch. Furthermore, parts must be arranged in the chamber in a specific manner.

Plasma nitriding equipment can be improved by placing resistance heating elements in the furnace wall and implementing pulsed mode plasma discharge with controlled pulse frequency and duty cycle\(^1\). However, even when operating state-of-the-art plasma nitriding systems equipped with multizone wall heaters and running in fully automated pulsed discharge mode, close attention must be paid to the uniformity of component geometry and the arrangement of parts in the chamber.

**ASP\^N process**

New plasma nitriding capabilities evolved with the development of the “active screen process,” in which the plasma discharge is applied to a mesh screen (active screen) surrounding the entire workload, rather than directly onto the components\(^2\). Highly reactive gas species are produced on the active screen and directed to the component surface. The principles of the ASP\^N process are based on the well known phenomenon of nitriding in “after glow\(^3\).” Another function of the active screen is to heat the workload by radiation, providing a very uniform temperature throughout the entire load independent of the complexity of component geometry. Schematics of equipment and experimental arrangement for the ASP\^N process and conventional DC plasma nitriding (DCPN) are shown in Fig. 1.

In ASP\^N, parts to be treated are placed on a worktable with a floating or negative (cathode) potential (bias) applied. Flow of the active species generated on the active screen and directed onto the components is effectively controlled using the bias voltage setting. Bias power...
applied to the workload in ASPN does not exceed 10% of the discharge power used in conventional plasma nitriding, which enables processing dense loads without the risk of hollow cathodes and arcing. Application of bias is essential in large industrial scale ASPN units to obtain the desired nitriding result[5].

Figure 2 shows a dense workload consisting of about 22,000 Type AISI 304 stainless steel piston rings that were treated in a single batch using the ASPN process. Treating a similar workload in a conventional plasma nitriding unit is not possible. Even using gas nitriding, surface activation of the high-alloy steel would present severe problems due to the influence of various uncontrollable parameters in the pretreatment step.

ASPN involves a large number of independent process parameters to produce a desired nitrided layer. Controlled plasma nitriding and nitrocarburizing in the ASPN process enables producing an entire spectrum of nitrided-layer structures—from a nitrided layer without a compound layer, through a mixed $\gamma'$ + $\varepsilon$ phase, to a pure $\varepsilon$-phase compound layer. Composition of the process gas and bias activation are the most important process parameters.

Varying the N$_2$-to-H$_2$ gas ratio in the N$_2$-H$_2$ plasma has a strong influence on compound-layer growth rate and structure up to the point of suppressing layer growth. Figure 3 shows the microstructure of the nitrided layer and the x-ray diffraction (XRD) spectrum of the compound layer of active screen plasma nitrided 1045 carbon steel, which has a single-phase $\gamma'$ layer thickness of about 5 $\mu$m.

Bias activation can also be used to control nitrogen concentration near the component surface. The role of bias power in the ASPN process is shown in Fig. 4. An increase in bias power leads to a significant improvement of compound-layer thickness. Surface hardness, hardness profile, and hardness depth are not dependent on compound layer thickness.

Nitriding with or without a very thin $\gamma'$ phase compound layer typically results in decarburization of the nitrided layer, which prevents precipitation of carbides along grain boundaries up to 70 to 100 $\mu$m below the surface. It is possible to produce a nitrided layer free of a compound layer without a reduction of edge hardness due to the fine control of nitriding potential in ASPN. Reduction of edge hardness is often an issue when nitriding using low nitriding potential.

Figure 5 shows a key advantage of ASPN—uniform nitriding a 304 stainless steel component with multiple 0.1-mm diameter drill holes, which confirms the high reactivity of the gas species generated at the active screen.

**ASPN process**

Active screen technology is also being applied to the controlled nitrocarburizing process, called active screen plasma nitrocarburizing, or ASPNC[5]. Typically, $\varepsilon$-carbonitride layers are produced in conventional plasma nitrocarburizing using CH$_4$ and C$_3$H$_8$ as carbon-bearing gases. The risk of cementite precipitation in the compound layer is still high even at 2% CH$_4$ admixture to the process gas. This significantly limits the ability to vary carbon potential of the process gas in conventional plasma nitrocarburizing compared with bath nitriding[6].

In the ASPNC process, the ability to vary bias and process gas composition (dual control) makes it possible to produce carbonitride layers comparable to those obtained in bath nitriding. Figure 6 shows a thick, cementite-free $\varepsilon$-carbonitride layer with 0.85 to 1.0 wt% carbon produced using the ASPCN process with 3% CH$_4$ admixture and a pressure of 400 Pa.

Both oxidizing and carburizing effects can be achieved by varying the CO$_2$-to-H$_2$ gas ratio in the process gas. Carburizing can also be controlled by means of the CO$_2$-to-N$_2$ gas ratio. Figure 7 illustrates the transi-
tion from a plasma oxinitriding to the plasma nitrocarburizing process.

Process gas for oxinitriding typically has a CO₂-to-H₂ gas ratio of 1. A thick compound layer and high nitrogen concentration are characteristic for the nitrided layer obtained with this process. Reducing the CO₂-to-H₂ gas ratio from 1 to 0.19 and increasing the CO₂-to-N₂ gas ratio from 0.15 to 0.4 significantly improves the carburizing effect of the process gas, which results in considerably higher carbon concentration in a thinner compound layer.

A goal of ongoing investigations is to develop sensor-supported process control in ASPN on the basis of results of different plasma diagnostic methods[7].

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