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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.

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Working Together to Maintain a Vibrant HTS

The importance of the ASM Heat Treating Society has never been greater as the heat treating industry moves forward in the 21st century. The health of the Society depends on strengthening areas including education, volunteerism, and membership.

We must bring more young people and new ideas into the heat treating industry and keep members at the cutting edge of technology, products, and processes. Education is the key. We must also engage and capitalize on volunteers. If we focus on these two priorities, the third priority—growing membership—will take care of itself. We need to work together to make HTS more appealing and valuable.

Ferrous and nonferrous heat treating is alive and well. Even though it’s a mature technology, there are continual breakthroughs in the field. Therefore, the need for continuing education remains. HTS is an important educator, focusing on midcareer development and preparing the next generation of heat treatment experts. Many companies need more qualified workers and can’t find them. The HTS Education Committee is focusing on updating HTS core content and curriculum guidelines to help two- and four-year colleges supply a workforce of trained, knowledgeable technicians. This content will be the basis for training in the classroom and online. For mid-career education, HTS offers the best technical information, both online and in print. We’re offering webinars and evaluating other multimedia education tools. For example, HTS launched its first mobile device app that serves as a quick reference companion, providing easy access to the content of the Heat Treater’s Guide.

If content is the lifeblood of an organization like HTS, then volunteers are its heart, pumping in new content to sustain the organization. From Materials Camps to technical meetings, from awards programs to membership outreach, everything our organization accomplishes is a result of passionate, committed volunteers.

Creating and maintaining a strong volunteer base involves three phases: Recruitment, Retention, and Recognition. New volunteers are best acquired through personal contact. Retaining them requires care and nurturing. Gradually increasing participation helps them develop their skills and keeps them engaged for the long run. Finally, the best thing you can do for volunteers is recognize, thank, and appreciate them. They don’t get paid in dollars, but instead with a sense of accomplishment, and that can’t happen without recognition.

Together we can continue to build a strong Society with a high value proposition for decades to come.

Roger A. Jones
President, Heat Treating Society

New Heat Treating App Released by ASM Heat Treating Society
Available for iPhone, iPad and Android

ASM International and the ASM Heat Treating Society released the Heat Treater’s Guide Companion, now available in the Apple and Google App Stores. The free app provides ready reference data on nearly 170 carbon and alloy steels including information on chemical composition, similar steels, characteristics, forging instructions, and recommended heat treating practices and processing sequences. The app is geared towards managers, metallurgists, engineers, technicians, and sales engineers so they can quickly and conveniently access the data.

The app can be used by itself or as a companion to the Heat Treater’s Guide print and online database products, which provide additional heat treating information such as representative micrographs, isothermal transformation diagrams, cooling transformation diagrams, tempering curves, and data on dimensional change.

“Heat Treating Society members and other industry professionals are requesting mobile access to data and information needed to accomplish work-related tasks. The Heat Treater’s Guide Companion is a first step in responding to that need, providing users with a fast, easy way to look up steel heat treating recipes,” explains Roger Jones, HTS President and Corporate President of Solar Atmospheres Inc. Download the app today!

For quick links to the Apple and Google App Store listings, go to http://hts.asminternational.org. For more information, contact linda.vermillion@asminternational.org, or 440/338-5151, ext. 5561.

Heat Treating Society Seeks Board Nominations

The ASM HTS Awards and Nominations Committee is seeking nominations for three Directors and a Young Professional Board Member. Candidates must be an HTS member in good standing. Nominations should be made on the formal nomination form and can be submitted by a chapter, council, committee, HTS member, or an affiliate society. The HTS Nominating Committee may consider any HTS member, even those who have served on the HTS Board previously. Nominations for Board Members are due March 1, 2014.

For more information and the nomination form, visit the HTS website at http://hts.asminternational.org and click on Membership and Networking and then Board Nominations; or contact Sarina Pastoric at 440/338-5151 ext. 5513, or email sarina.pastoric@asminternational.org.
27th HTS C&E a Winner in Indy

The 27th ASM Heat Treating Society Conference and Exposition was a major success in Indianapolis in September, attracting more than 2000 attendees from the heat treating industry and featuring a sold out Expo with more than 180 exhibiting companies. The attendance reflected a 16% increase from 2011 and 28% increase from 2009.

A highlight of Heat Treat 2013 was the “Master Series” sessions, special programming that focused on heat treating pioneers whose research transformed heat treating technology. Attendees were treated to lectures by current experts in the field on the contributions and impact of past heat treating “giants” Walter Jominy, Marcus Grossmann, and Edwin Northrup. The event also offered a full technical program covering a broad scope of heat treating technology, networking opportunities, and a firsthand look at equipment, supplies, and services from exhibitors.

HTS and the American Gear Manufacturers Association will co-locate again in October 2015 at the 28th ASM Heat Treating Society Conference and Exposition, returning to the birthplace (in 1913) of the Steel Treaters Club in Detroit. Persons interested in presenting a paper at the event should visit the HTS website in December 2013 for more information about abstract submissions. Companies interested in reserving booth space should contact Kelly Thomas, at kelly.thomas@asminternational.org or 440/338-1733.

HTS Members Honored

John D. Hubbard, CEO (retired), Bodycote plc, headquartered in Macclesfield, Cheshire, UK, received the 2013 George H. Bodeen Heat Treating Achievement Award. Hubbard was 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.”

Jiandong Liang, who recently received his Ph.D. in mechanical engineering from Louisiana State University, Baton Rouge, received the 2013 HTS/Bodycote Best Paper in Heat Treating Award. The paper, of which he is the primary author, is entitled “Localized Surface Modification on 1018 Low Carbon Steel by Electrolytic Plasma Process and its Impact on Corrosion behavior.”

Three Heat Treating Society members shown here were inducted into the ASM Class of Fellows at the MS&T’13 Awards Ceremony on October 29 in Montreal; Award presented by ASM President Gern Maurer.

Stephen J. Mashl, right, research professor at Michigan Technological University, Houghton, and head of Z-Met Inc., a materials consulting company, is recognized “for industrial and academic contributions and leadership in the fields of heat treatment, powder metallurgy processing, and hot isostatic pressing technologies.”

Satyam S. Sahay, FASM, right, technology manager, John Deere Technology Center India, Pune, is recognized “for successful implementations of model-based optimization in heat treating industries; outstanding research in the area of process modeling and non-isothermal phase transformations; and for significant contributions towards professional societies, journal boards, and academic institutions.”

Robert Hill, president, Solar Atmospheres of Western PA, Hermitage, is recognized “for expanding the applications and technical knowledge of vacuum heat treating titanium for the future of lightweight and energy-efficient commercial and military airframes.”

From left to right: Tom Clements, Hubbard, and Terry Brown.

From left to right: Tom Clements, Liang, and Eric Hutton (VP Operations – Automotive, North America, Bodycote Thermal Processing).
Submit Papers for ASM HTS/Bodycote ‘Best Paper in Heat Treating’ Contest

This 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.


Submissions should be sent to: Sarina Pastoric, ASM Heat Treating Society, 9639 Kinsman Rd., Materials Park, OH 44073, 440/338-5151 ext. 5513, sarina.pastoric@asminternational.org.

ASM Mini-Materials Camp held during HTS 2013 in Indy

More than 200 students and nine teachers from seven local schools attended the ASM Mini-Materials Camp held during the 2013 Heat Treating Conference and Exposition in Indianapolis. Thanks to the ASM HTS Board for their support of the program and to the volunteer presenters for providing the students a fun and educational experience at the mini-camp.

Bernard receiving the ASM Distinguished Life Membership Award

William J. (Bill) Bernard Jr., FASM, president and CEO of Surface Combustion Inc., Maumee, Ohio, was recognized at the MS&T’13 Awards Ceremony on October 29 in Montreal “for unwavering dedication to the advancement of the metallurgical/heat treating industry and exemplary leadership, vision, and professional service supporting industry organizations and professional societies.”

Plan your conference today! This year’s conference will bring together modeling specialists in materials science, solid mechanics and fluid mechanics as well as numerical simulation to discuss the state of the art from both theoretical and applied viewpoints.

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In the heat treating industry, finding the right people to fill jobs is a challenge. A shortage of metallurgists, heat treat specialists, and engineers is creating a difficult void. The result is a growing concern that as the current generation of heat treating professionals retires, there will not be sufficient future talent to take over. To bridge this gap, industry leaders are turning to Worcester Polytechnic Institute’s (WPI) Center for Heat Treating Excellence (CHTE). Together, they are training today’s students to be tomorrow’s heat treating experts.

How does it work? It starts with the proven theory and practice philosophy that is at the heart of WPI’s approach to education, and it concludes with a structured CHTE internship program that gives students hands-on application experience in the heat treating industry. The overall mission of CHTE is for industry and university researchers to work together to solve business challenges and improve manufacturing processes. Research is a large part of this mission, and getting students involved in current research projects and training them to be future heat treating professionals is a big part of the value that CHTE brings to its industry members.

**Internship program benefits**

Benefits of the internship program that industry draws from include:

- Members work with mature engineering talent capable of taking on responsible assignments in a professional work environment (all interns have at least a B.S. degree).
- For-credit thesis and graduate project work can be oriented toward the program interests of the sponsoring member. This provides results in areas that might not otherwise be addressed by regular full-time staff members.
- The program helps to maintain an infusion of new talent. Students and employers make early assessments of each other without making initial long-term commitments.
- Valuable links are created between the academic and professional worlds. The program strengthens employers’ contact with new ideas, viewpoints, and latest generation technologies.
- The program improves access to CHTE facilities and capabilities, including faculty expertise, experimental facilities, computer support capabilities, databases, and library holdings.

CHTE coordinates the process of bringing students and employers together. While placement is not guaranteed, every effort is made by the center to find appropriate students to meet specific member requests. Final matching and selection are accomplished with direct interviews between the sponsor and student. If desired, a representative of the sponsoring member organization can serve on the student’s thesis committee along with three WPI faculty members.

The key to success centers on regular communication and evaluation among students, sponsors, and faculty. Sponsors are asked to evaluate students’ performance, while students are asked to evaluate the internship experience during and after specific work assignments.

“We applied information from a CHTE gas carburizing optimization project into our process, which resulted in improved results. We also hired the CHTE intern who worked on the project.” - Michael Pershing, Caterpillar Inc.

For more information about CHTE and its member services, visit www.wpi.edu/+chte.
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- Programmable serial cutting and uniform serial cutting
- 36 W x 22 D x 8in H [914 x 558 x 203mm] cutting chamber
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Visibility
- Three large clear windows provide ample viewing area
- LED lighting illuminates chamber during setup, fixtureing and sectioning

Simple Controls
- Select cut type, enter feed rate, Y cut length, MAC depth, Z cut depth and pulse option where required or use saved methods
- Joysticks quickly position wheel and table
- Ergonomic design keeps controls close without causing operator fatigue

Advanced Features
- Touch Detect senses contact between the wheel and sample instantly switching from rapid advance to programmed feed rate saving valuable time
- Wheel Size Detection alerts operator when the cut length is too long for the remaining wheel or when conditions exist that allow the table to be cut

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Researchers are continually looking for ways to enhance materials performance by developing both new materials and processing methods including nontraditional fabrication/processing/manufacturing techniques, such as laser surface modification (LSM). Lasers have emerged as a versatile tool in a wide variety of industrial applications[1]. Newer, more efficient lasers (especially fiber lasers) along with advancements in automation techniques, enable expanded use of this technology as a cost-effective processing and manufacturing tool to enhance materials surface and subsurface performance[2], beyond conventional applications such as drilling, cutting, and welding. LSM plays a key role in improving many materials properties as shown in Fig. 1[1,3–5]. This article provides a brief overview of LSM techniques and their use in a wide variety of engineering applications at multidimensional scales (nano to meso) to meet ever increasing industrial demands.

The effectiveness of LSM can be further improved using integrated computational methodologies such as finite-element modeling (FEM) and optimization techniques, such as analysis of variance (ANOVA). These integrated approaches overcome difficulties associated with in situ measurement (e.g., temperature, melt-pool geometry, and concentration gradient) encountered during laser processing, because heating/melting/vaporization occur in a small confined zone for a very short time. In addition, LSM is influenced by many factors such as laser processing parameters (e.g., power, beam scanning speed, and overlap between successive laser tracks), materials thermal properties, heat transfer phenomena, and convection-induced mixing in the molten pool. These factors can be addressed by using optimization approaches, such as regression analyses and ANOVA, in conjunction with FEM-based computational simulation and experimental studies.

The authors adopted integrated computational and experimental approaches (Fig. 2) to optimize LSM parameters based on targeted values for a few key attributes, such as hardness, microstructure, dilution, and corrosion/wear properties[6,7]. LSM enhances surface properties either by altering surface metallurgy or surface chemistry, or by adding a surface layer of strategic materials to meet application requirements without losing the physical characteristics of the bulk material, as shown in Fig. 3[3–5].

**Altering surface metallurgy**

In the past, strengthening mechanisms (e.g., solid-solution hardening, grain refinement, and solid-state phase transformation) were developed by altering surface metallurgy to yield higher surface strength, hardness, toughness, and ductility for both crys-
Advanced laser processing techniques are designed to alter the microstructure and surface chemistry of materials to improve their mechanical properties and performance. These techniques can lead to significant enhancements in material properties, such as increased hardness, improved wear resistance, and enhanced corrosion resistance.

**Altering surface chemistry**

This approach primarily processes the material surface under a reactive atmosphere (e.g., carbon, methane, or nitrogen) to promote carburization and nitrification. It is achieved by diffusing carbon/nitrogen interstitial atoms into the crystal lattice creating a barrier for dislocation/slip, thus increasing mechanical strength. Some drawbacks associated with conventional methods are longer processing times, toxic conditions, and large dimensional deviations. LSM overcomes these limitations and produces carburization and nitrification through complicated interactions between the laser beam, material surface, enclosure gas, and plasma/plume.

For example, titanium nitride (TiN) is formed on titanium and Ti alloys to enhance tribological, corrosion-resistant, and biological properties. Laser-nitrided Ti-6Al-4V has a lower corrosion rate than untreated samples (0.019 µm/y compared with 2.627 µm/y, respectively) under simulated body fluid solution (a mixture of H2O, NaCl, NaHCO3, KCl, K2HPO4·3H2O, MgCl2·6H2O, CaCl2, and Na2SO4).

**Adding a surface layer of strategic materials**

In this method, surface and subsurface properties are altered to meet requirements without sacrificing bulk material characteristics by adding just the right amount of surface layer of strategic materials (e.g., expensive, scarce metals and ceramics) on the bulk material. The bulk material is alloyed with additive materials (preplaced or powder feeder) by using the laser beam as a heat source. The alloyed region is confined to a shallow depth. Rapid solidification rates produce a sound, metallurgically bonded coating with a high concentration of key elements in the alloyed region along with favorable microstructures.

Such microstructures with metastable phases or extended solid solubility characteristic of rapid solidification cannot be obtained using conventional methods. Also, due to localized heating, laser processing has advantages such as negligible distortion, low porosity, and noncrystalline (or amorphous) ferrous and nonferrous materials for a wide variety of industrial applications.

**Figures**

- Fig. 4 — Laser surface heat treating: (a) schematic of process, (b) cross-sectional microstructure of laser processed AZ31B magnesium alloy, (c) as-received AZ31B with 50 Vickers hardness, and (d) refined grain structure in laser heat treated AZ31B with 150 Vickers hardness.
- Fig. 5 — Laser nitriding: (a) schematic of process, and (b) cross-sectional SEM back-scatter micrograph shows the distinct TiN layer along x–y cutting plane.
- Fig. 6 — Laser surface alloying: (a) schematic of process, and (b) cross-sectional SEM back-scatter micrograph showing the TiC composite coating (brighter contrast) on aluminum (darker grey contrast).
ity, high hardness, narrow heat affected zone (HAZ), and reduced cracking susceptibility.[11, 12]

Among other nonequilibrium processes (e.g., sputter deposition, ion implantation, and vapor deposition), LSM is more beneficial because it does not require high in-process vacuum, can produce complex structures, and can fabricate thick coatings (>50 μm). Therefore, laser surface alloying, laser cladding, and composite coating based on LSM provide a new path to enhance surface resistance to corrosion, abrasion, and wear. For example, a hard titanium-carbide (TiC)/Al composite coating (450 kg/mm² Knoop hardness) is formed on aluminum (100 kg/mm² Knoop hardness) to enhance mechanical and tribological properties (Fig. 6).

Acknowledgement: This work was supported by the National Science Foundation (NSF-CMMI 1010494 and NSF-CMMI 0969249) and American Chemical Society Petroleum Research Fund (ACS PRF 50283-DNI10). The article is based in part on the masters/doctoral research work of Hitesh Vora, Ravi Shanker Rajamure, Shrvana Katakam, and YeeHang Ho at the University of North Texas.

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References
Flash processing [FP] is an innovative steel heat treatment based on the concept of rapid thermal cycling to create a mixed microstructure consisting of martensite, bainite, and carbides. It is generally understood that the ductility of a material decreases as strength increases. However, the unique microstructure produced by FP results in extremely high strength while maintaining high ductility for the given strength. These properties vary for different alloys, reaching an ultimate tensile strength of 1.99 GPa [288.6 ksi] while maintaining 10.2% total elongation for flash processed AISI 4140. Figure 1 compares this unusual combination of strength and ductility with those of common advanced high-strength steels. A wide range of steels have been flash processed including AISI 1010, 1020, 1050, 4130, 4140, 6150, 8620, and DP800. Plate dimensions up to 6.35 mm × 609 mm × 3657 mm (0.25 × 24 × 144 in.) and tubular dimensions up to 50.8 mm in diameter and 3.05 mm wall thickness (2 and 0.12 in.) have been processed.

This article discusses the specifics of flash processing, microstructural evolution during processing, the industrial impact of flash processed materials, and ongoing research to further extend the capabilities of FP steels.

**Processing specifics**

Flash processing is an extremely rapid heat treatment with a total process time of less than 10 seconds. A schematic of the process is shown in Fig. 2. Steel enters an induction heating unit, which heats the material at a rate of approximately 400°C/s to a temperature between 1000° and 1100°C (1830° and 2010°F), depending on the initial microstructure and steel composition. Unlike traditional heat treatments, the material is quenched after a short hold (about 2 s) above the $A_C^3$ temperature. Water quenching in either a constantly agitated bath or by multiple jet spray produces cooling rates as high as 3000°C/s. A low-temperature, short-duration tempering treatment is often used to increase ductility. The process produces a well-controlled, mixed microstructure consisting of martensite, bainite, and carbides.
Flash-processed steel exhibits very minimal shape distortion.

**Microstructural evolution**

Flash-processed microstructures depend on the initial microstructure and nonequilibrium conditions resulting from high heating rates, short hold times, and high cooling rates. A schematic of the microstructural evolution during different stages of flash processing of AISI 8620 steel tubing is shown in Fig. 3.

Prior to rapid heating (Region I), the initial microstructure consists of ferrite grains with carbides. For FP to be successful, carbides must be chromium-enriched (Fe, Cr)\(_3\)C carbides in the fully spheroidized condition. This initial microstructure leads to slow dissolution of carbides during the short time spent above the carbide solvus temperature. It is critical that the chromium-enriched carbides do not completely dissolve during processing.

The steel is rapidly heated above the \(A_{C3}\) temperature (Region II), causing austenite to nucleate and begin consuming ferrite grains. While rapid heating may cause the \(A_3\) temperature to exceed the equilibrium value, the peak temperature is higher than the nonequilibrium \(A_{C3}\) transformation temperature.

During the brief hold at peak temperature (Region III), growing austenite completely consumes previous ferrite grains and begins to dissolve carbides. However, carbides do not completely dissolve due to sluggish diffusivity of substitutional elements such as chromium. Further, the short hold time at peak temperature prevents carbon from the dissolving carbides to completely homogenize within austenite grains. These conditions lead to carbon concentration gradients; austenite with regions of high carbon near partially dissolved carbides and regions of low carbon far from the carbides.

The material is rapidly quenched (Region IV). Due to the carbon concentration gradients, regions of high carbon undergo a martensitic transformation, while regions of low carbon undergo a bainitic transformation. Martensite is the primary strengthening constituent and bainite provides ductility, resulting in a balance of strength and ductility unique to flash processing.

The final microstructure after FP was characterized using transmission electron microscopy, single-sensor differential thermal analysis (SSDTA), and microindentation hardness. A transmission electron micrograph of FP AISI 8620 (Fig. 4) shows both martensite and bainite. However, it is difficult to quantify the fraction of martensite and bai...
martensite and bainite.

Fig. 5 — SSDTA curve shows two transformation events representing the formation of martensite and bainite.

In armor applications, the U.S. Army Research Development Engineering Com-
mend reports that FP 4130 potentially can reduce product cost and weight and enhance mechanical performance. Metallic armors typically work best against bullets and blast fragments. However, ballistic tests at the U.S. Army Aberdeen Test Center show that 6.3-mm thick FP 4130 with a 50 kg/m² area density was the highest performing metallic armor against bullets and blast fragments at that mass. The material stopped higher velocity armor piercing bullets and blast fragments better than more costly aluminum, magnesium, and titanium armors now in use.

FP steel has good weldability because it does not require pre- or post-weld heat treating required for other armors with similar ballistic resistance. Softening occurs in the HAZ (also common in Al, Ti, and Mg armors), which is detrimental to ballistic resistance, but vehicles are often built with overlapping joints, which could negate softening effects. In addition, due to its reduced thickness, FP steel can be welded in a single pass compared with other lower density materials, which may necessitate multipass welding due to increased thicknesses required to provide the same strength. FP steels may be easier to fabricate and handle due to greater familiarity with the steel grades versus other materials.

In the automotive industry, many OEMs and Tier 1 automotive suppliers find that FP steels reduce component weight without compromising performance. Hyundai Motor Group recently tested FP steels for use in applications such as armor, and automotive components requiring good crash resistance would benefit most.

In armor applications, the U.S. Army Research Development Engineering Com-

Industrial impact

The properties produced using flash processing could have significant impact in various industrial applications. Those requiring high strength and toughness, such as armor, and automotive components requiring good crash resistance would benefit most.

In the automotive industry, many OEMs and Tier 1 automotive suppliers find that FP steels reduce component weight without compromising performance. Hyundai Motor Group recently tested FP steels for use in applications such as vehicle door-side impact beams. In a drop weight test with a mass of 320 kg and an impact velocity of 5 m/s[^2], FP tubing outperformed the industry standard boron-steel tubing by 20% in total bending energy absorbed, and by 15% in resisting bending force. Mathematical modeling shows FP steel in automotive bumpers and trailer hitches meet OEM performance requirements at 67% of the weight of current materials.

In armor applications, the U.S. Army Research Development Engineering Com-

Current developments

Research in flash processing is currently underway to fully exploit the potential of FP steels and their applications. Researchers at The Ohio State University are examining FP steel weldability with respect to strength and ballistic requirements, exploring strategies to mitigate softening at elevated temperatures, and creating a model with the ability to predict material properties for different applications. HTPRO

References


For more information: S.S. Babu, Department of Mechanical, Aerospace & Biomedical Engineering, The University of Tennessee, Knoxville, sbabu@utk.edu, www.engr.utk.edu.
LOW-TEMPERATURE SURFACE HARDENING OF STAINLESS STEEL

LOW-TEMPERATURE SURFACE HARDENING OF STAINLESS STEEL PROVIDES THE REQUIRED PERFORMANCE PROPERTIES WITHOUT AFFECTING CORROSION RESISTANCE.

Thomas L. Christiansen and Marcel A.J. Somers
Technical University of Denmark, Lyngby

Stainless steels rely on the presence of chromium in solid solution, which allows the development and maintenance of a passive layer at the surface. Nitriding, carburizing, and nitrocarburizing are generally not considered good practice, because processing in the conventional temperature range between 490° and 950°C leads to chromium nitride and chromium carbide precipitation. While this provides a hardening effect, it is highly detrimental to corrosion properties. Since the mid-1980s, several processes were developed that enable low-temperature surface hardening of stainless steel at temperatures below 440°C.

The first deliberate surface hardening of stainless steel was achieved by a process known today as Kolsterizing[1], a method ostensibly inspired by corrosion phenomena observed in liquid-metal fast breeder reactors[2,3]. About the same time, seminal work by Zhang and Bell[4] on plasma nitriding of stainless steel was published. Throughout the 80s and 90s, the development of low-temperature surface hardening of stainless steel relied largely on plasma-based techniques, while in the past 10 years in particular, gaseous processing was developed and commercialized.

This article describes fundamental and technological aspects of low-temperature surface hardening (LTSH) of stainless steel. The results shown are taken from the authors’ research during the past 15 years.

LTSH principles

The ‘TTT’ diagram in Fig. 1 demonstrates the combination of allowable treatment time at low temperature before precipitation of Cr-based nitrides or carbides occurs. In this temperature range, interstitially dissolved nitrogen and carbon can diffuse over a relatively long distance, while substitutional dissolved metallic elements can be considered stationary. Consequently, nitride or carbide development proceeds so slowly that a nitrogen or carbon rich case free of chromium nitrides/carbides develops. In the early days of LTSH, the case produced was considered a new phase, dubbed the S phase[5]. Recent research shows that no new phase develops, but rather LTSH of austenitic stainless steels produces a case that is essentially a solid solution of high amounts of nitrogen and/or carbon in austenite where interstitial atoms group around chromium atoms[6–7]. Therefore, it is incorrect to refer to the case produced as S phase; expanded austenite is preferred.

The hardening effect that occurs by dissolving nitrogen and carbon at low temperature in stainless steel is not due to nitride or carbide formation. Rather, solution of high amounts of interstitial atoms in the austenite lattice provides effective hardening.

Process technology and applications

Plasma processes, apart from the proprietary Kolsterizing process, have a unique advantage over gaseous processing, because surface activation (removal of the passive film through sputtering) is an inherent step of such treatments. The (temporary) removal of the passive layer is necessary to allow surface penetration of nitrogen and carbon from the nitriding/carburizing atmosphere.

Gaseous processing enables the highest flexibility, as well as straightforward monitoring and control. For a long time, it appeared that gaseous processing of stainless steel was possible only by in-situ removal of the passive layer in aggressive halogenides[8,9], or after ex-situ deposition of a metal layer promoting dissociation of the gas components and protecting the surface against (re)passivation during storage and treatment[10,11]. Later, robust gaseous treatments were developed based on gas mixtures that can both remove the passive layer and provide the nitrogen/carbon to the stainless steel surface[12–14]. Expanite, a company co-founded by the authors and Thomas Strabo Hummelshøj, works exclusively with gas mixtures that have this dual ability.

Figure 2a shows the case produced during gaseous nitriding of austenitic stainless steel. The corresponding nitrogen content profile, hardness, and residual stress level are shown in Fig. 3. Dissolution of a huge amount of nitrogen leads to an appreciable increase in surface hardness and high compressive residual stresses, which arise due to austenite lattice expansion in the nitried case. High surface hardness contributes to improved wear and galling performance, while residual stress enhances fatigue performance. During nitriding of austenitic stainless steel, an almost featureless case develops at the surface (Fig. 2a), indicating that the zone is more difficult to dissolve by the etching reagent than the unaffected austenite.

Similar results are obtained with carburizing (Fig. 2b), although less carbon can be dissolved resulting in lower increase in hardness and residual stress. The choice of nitriding or carburizing depends on the application, as both processes have advan-
tages. For example, dissolved nitrogen has a positive effect on corrosion resistance (e.g., pitting). Carburizing produces an advantageous shallow case-core transition because the affinity of chromium for carbon is not as high as for nitrogen. By comparison, nitriding yields a relatively sharp case-core transition. A gradual transition in hardness/composition can be tailored by adopting gaseous nitrocarburizing or the two-stage process of carburizing followed by nitriding\[16\]. These processes produce a hardened case consisting of a hard zone of nitrogen-expanded austenite and a zone of carbon-expanded austenite underneath (Fig. 2c).

For the case of heavy surface loading, austenite load bearing capacity should be enhanced further. The simplest solution is to prolong the duration of the nitriding/nitrocarburizing treatment. However, this enhances the risk for precipitation of chromium nitrides and associated loss of corrosion resistance. In such demanding applications, the low-temperature surface hardening treatment can be preceded by a high-temperature solution nitriding treatment\[18\], which dissolves a relatively low amount of nitrogen into austenite up to a depth of several millimeters. Cooling from the solution nitriding should be done carefully to prevent development of chromium nitride (Cr$_2$N or CrN) precipitation (see Fig.1).

Alloy grades other than austenitic stainless steels can be treated. Most stainless steel types including austenitic, ferritic, duplex, martensitic, and precipitation-hardening (PH) grades can develop a surface case of nitrogen and/or carbon-expanded austenite by undergoing gaseous nitriding, carburizing, and nitrocarburizing treatments. Expanded austenite can also be formed in other types of (similar) alloy systems, such as many Ni-base alloys. For example, Ni-base superalloys such as the Nimonic series can be nitrided, but low temperatures (360–400°C) are required to suppress formation of unwanted CrN[17]. Also, martensitic and austentic PH steels can be nitrided and simultaneously bulk hardened[18, 19].

**Summary and outlook**

Surface hardening of stainless steel can be achieved by low temperature nitriding, carburizing, and nitrocarburizing by transformation of the surface into nitrogen and/or carbon-expanded austenite. Gaseous processing provides a high degree of tailorable hardness of the hard surface case enabling tailoring of materials properties, and therefore, performance. Most stainless steels and similar alloy systems can be surface hardened by means of gaseous processing.

Today’s stainless steel alloys treated using LTSH are designed for purposes other than surface hardening. New stainless steel alloys with compositions tailored for optimal LTSH will further expand the applicability of low-temperature surface hardening.

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**References**


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**For more information:** Marcel A.J. Somers, Prof. and Section Head – DTU Mechanical Engineering, Technical University of Denmark, Productionstorvet Bldg. 425, 2800 Kgs. Lyngby, Denmark; somers@mek.dtu.dk; www.mek.dtu.dk.

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**Fig. 2 —** Cross sections of (a) AISI 316 after nitriding at 445°C for 22 h in a gas mixture containing 60% NH$_3$ and 40% H$_2$, (b) AISI 316 nitrocarburized in acetylene at 520°C for 3 h (the transition from core to hardened case is more diffuse than for nitriding), and (c) cold-worked AISI 304 nitrocarburized at 420°C for 19 h (the nitrocarburized case is subdivided in a zone of nitrogen-expanded austenite and a zone of carbon-expanded austenite below).

**Fig. 3 —** Nitrogen content, hardness, and residual stress in AISI 316 after nitriding at 445°C for 22 h in a gas mixture containing 60% NH$_3$ and 40% H$_2$.\[17\]
Gas quenching has several benefits compared with other quench systems. It is the only dry quench that exists and, therefore, it eliminates all environmental or safety problems connected with liquid quenching. This article examines why defining gas quenching in bar pressure no longer applies, why a new definition is needed, and how this definition enables a better understanding of which steel and what cross section can be hardened via gas quenching.

A hardened core or hardened surface for metals is accomplished by heating to a sufficiently high temperature and rapid cooling (quenching) to room temperature. Quenching uniformity is of the utmost importance, which requires addressing quench system inadequacies that may be detrimental to process results. Dry gas quenching meets industry needs more efficiently than liquid quenching.

**State-of-the-art quenching**

Heat treating ferrous metal parts involves heating to a temperature above the upper critical temperature (A_c3) into the austenite region of the phase diagram, which depends on alloy composition. Parts are rapidly cooled by a quenching fluid or gas, so that the microstructure transforms into the harder martensite phase. The cooling rate must be fast enough to minimize formation of softer bainite and pearlite phases, which negatively impact mechanical properties. The key to accomplishing the transformation is uniform heat removal from the part surface. Figure 1 shows a representative continuous cooling curve for a ferrous alloy.

Quenching oils have a range of quenching severity depending on their physical properties, especially viscosity. Oil, like water, exhibits a pronounced vapor phase upon quenching followed by a nucleate boiling phase with a very rapid heat transfer in the temperature range of 570° to 1110°F (300° to 600°C). The three cooling stages of an oil quench are shown in Fig. 2.

These stages might not occur at all part locations at the same time. During the oil-quench nucleate boiling phase, extremely high instantaneous heat transfer coefficients can be achieved. This is an advantage in the temperature range where pearlitic transformation occurs, an advantage not shared by gas quenching. However, with the breakdown of the vapor phase at the onset of boiling, the so-called Leidenfrost effect occurs.

Gas quenching is a pure, convective type single-phase quench. Gas species, pressure, and velocity are the main controlling factors. Gas-quench cells are equipped with powerful fans capable of injecting gases (typically up to 20-bar positive pressure) in conjunction with heat exchangers using chilled water to quickly remove heat from the quenching gases. The most common quenching media is high-pressure nitrogen gas. A major benefit of the more uniform cooling rate of gas quenching is lower part distortion. High-pressure gas quenching can sometimes eliminate the need for post-heat treatment straightening or clamp-tempering operations, reduce grind stock allowances and hard machining, and replace more costly processes, such as press quenching.

**Comparison of oil and gas quench rates**

Gas quenching intensity can be adjusted to match the cooling rate of liquid quenching as shown below.

The mean heat transfer coefficient over total cooling in quenching a full load in a high-volume gas flow from 1650° to 212°F (900° to 100°C) can be matched to liquid quenching. Thus, the overall cooling rate from start to finish for quenching in 10-bar nitrogen gas (gas velocity = 10 m/s) compares to quenching a full...
load in a molten salt bath, and a 40-bar hydrogen gas quench matches the average cooling rate of an agitated, high-grade fast oil quench. However, it is not accurate to conclude that quenching in 40-bar hydrogen gas produces the same metallurgical result with respect to hardness, case depth, and microstructure. The temperature and time dependence of the cooling rate is totally different in a liquid with pronounced nucleate boiling phase and pure convection cooling. Figure 4 illustrates this effect by comparing the temperature-dependent cooling rates of gas and oil quenching.

Even with the highest cooling rate possible (close to 120°F/s or 50°C/s) in high-pressure gas quenching, peak cooling in gas does not come close to that of oil in the nucleate boiling phase, where maximum values of 212°F to 300°F (100°C to 150°C/s) are possible. As these high cooling rates during nucleate boiling occur in the important phase of steel quenching (the ferrite and pearlite noses of CCT diagrams), quenching of low-hardenability steel in oil produces a pure martensitic structure. By comparison, high-pressure gas quenching produces a hardened structure containing pearlite and ferrite, despite the fact that average cooling rates of both quench systems are equal. Thus, there is a large uncertainty for gas quenching in predicting hardness and structure of quenched steel components.

A procedure developed by Ipsen to predict the hardness and structure after gas quenching makes use of the necessary cooling rate in the temperature region of the pearlite and ferrite formation (i.e., between 1470°F and 930°F (800°C and 500°C)). If the necessary cooling rate to avoid pearlite and ferrite formation is reached or exceeded during a given point in the quenching process, you can be sure about achieving the required results.

Defining these cooling rates from a given CCT diagram leads to the question: What is the necessary heat transfer coefficient for given workpiece diameters to reach the specified cooling rate in the core of the pieces? Solving the heat conduction equation for a given problem or respective approximation formulas enables estimating the necessary heat transfer coefficient. Table 1 shows the results of such estimation. Therefore, a more useful method is empirical measurement of the heat transfer coefficient in each gas quench system, a task easily performed using a specialized tool such as the Ipsen flux sensor.

**Conclusion**

In many cases, the first attempt to gas quench a component does not lead to reduced distortion because load and gas flow considerations are not optimized. Using existing knowledge about laminar and turbulent gas flow together with gas quenching adapted and adjusted to load configuration nearly always leads to much lower distortion compared with oil and salt bath quenching.

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<p>| Table 1 — Correlation of Material, Cooling Rate, and Heat Transfer Coefficient |
|-------------------------------------|---------------------|---------------------|---------------------|</p>
<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Core hardness</th>
<th>Cooling rate, °F/s (°C/s)</th>
<th>Heat transfer coefficient, α</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>λ</td>
<td>20 mm diam.</td>
</tr>
<tr>
<td>55NiCrMoV6</td>
<td>&gt;57 HRC</td>
<td>38.3 (3.5)</td>
<td>0.85</td>
</tr>
<tr>
<td>X210Cr12</td>
<td>&gt;64 HRC</td>
<td>40.64 (4.8)</td>
<td>0.63</td>
</tr>
<tr>
<td>90MnV8</td>
<td>&gt;64 HRC</td>
<td>42.08 (5.6)</td>
<td>0.54</td>
</tr>
<tr>
<td>42CrMo4</td>
<td>&gt;54 HRC</td>
<td>140 (60)</td>
<td>0.05</td>
</tr>
<tr>
<td>42CrMo4 mod</td>
<td>&gt;54 HRC</td>
<td>38.84 (3.8)</td>
<td>0.80</td>
</tr>
<tr>
<td>16MnCr5</td>
<td>&gt;300 HV</td>
<td>59 (15)</td>
<td>0.20</td>
</tr>
<tr>
<td>20MoCr4</td>
<td>&gt;300 HV</td>
<td>73.4 (23)</td>
<td>0.13</td>
</tr>
<tr>
<td>15CrNi6</td>
<td>&gt;300 HV</td>
<td>39.2 (4)</td>
<td>0.75</td>
</tr>
</tbody>
</table>

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**Fig. 2** Three cooling stages of an oil quench.

**Fig. 3** Comparison of cooling rates of high-pressure gas quench and cold oil quench.

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PREPUBLICATION PRICE: $249, MEMBER $189
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Coverage on heat treating in the ASM Handbook series is being expanded into several volumes, and ASM Handbook, Volume 4A, Steel Heat Treating Fundamentals and Processes is the first of multiple volumes on heat treating. Volume 4A introduces the basics of steel heat treating and provides in-depth coverage of the many steel heat treating processes. Coverage includes:

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