HTS Heat Treating Society
ASM INTERNATIONAL

HTPRO
BUSINESS AND TECHNOLOGY FOR THE HEAT TREATING PROFESSIONAL

NOVEMBER-DECEMBER 2014 • VOLUME 2 • ISSUE 4

# BORIDING FOR WEAR RESISTANCE

PAGE 7

# NEW TECHNICAL RESOURCE FOR INDUCTION HEATING/ HEAT TREATING PRACTITIONERS

PAGE 11

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## Keeping Your Vacuum Furnace System Healthy and Pumping

Just as is it is important to keep your heart healthy and pumping, it is crucial to keep your vacuum furnace system healthy and pumping. Get the best performance out of your vacuum furnace by selecting the most appropriate pumping system for your process and following a few simple tips.

Let's start with the basics. In order to evacuate atmospheric pressure from the vacuum chamber to the required ranges for your specific processes, vacuum furnace systems must utilize various types of pumping system combinations. It is essential to maintain the pumping system as specified in the operator's manual, taking into consideration any special accommodations the specific process being conducted may require.

Read the full article at **www.IpsenUSA.com/Pumping** to learn more about maintaining your pumping system and preventing a pump's worst enemy.

Scan this code to read the article.

## Enhancing Your Atmosphere Furnace's Process and Part Quality

Heat treatment is consistently viewed as a critical step for adding value to the parts produced. This is why, when producing quality parts in atmosphere furnaces, it is essential to follow these tips for utilizing the carburizing and quenching processes, as well as applicable modern technology.

To start, when carburizing and quenching parts in a batch atmosphere furnace, it is essential to achieve uniformity of temperature and gassing, optimize flow and aim for uniform quench speeds. Ipsen's Carb-o-Prof® control software helps maintain balance by regulating, documenting and archiving the carburizing processes in atmosphere furnaces. The software is able to adapt the process to unforeseen events, preventing the potential waste of parts and resources.

Read the full technical article at **www.IpsenUSA.com/AtmosphereFurnaceTips** to view tips for enhancing processes and producing high-quality parts with reduced distortion.

Scan this code to read the article.

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## DEPARTMENTS

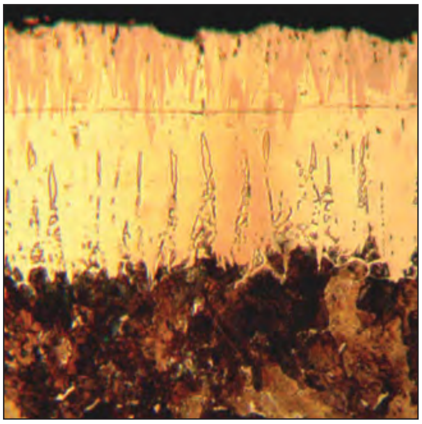


## Editorial Opportunities for *HTPro* in 2015

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

| | |
|---|---|
| **March** | Thermal Processing in the Aerospace Industry |
| **June** | Testing and Control |
| **October** | Thermal Processing in Automotive Applications |
| **November** | Atmosphere/Vacuum Heat Treating |

To contribute an article to one of the upcoming issues, please contact Frances Richards at frances.richards@asminternational.org. To advertise, please contact Erik Klingerman at erik.klingerman@asminternational.org.



**ABOUT THE COVER:**
*Dual-phase layer consisting of $Fe_2B$ (lighter colored deep "teeth") and FeB (darker colored shallow teeth) contains stress-related cracks that run parallel to the material surface. Bluewater Thermal Solutions, bluewaterthermal.com.*

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# TMI ATC Project Making Headway

The Thermal Manufacturing Industries Advanced Technology Consortium (TMI ATC) AMTech project led by ASM International was formed to lead and coordinate a national effort that identifies common thermal manufacturing needs across industries and solicits input from key stakeholders. Roadmapping workshops, such as those held during October at Furnaces North America in Nashville and at the MS&T conference in Pittsburgh, will identify technologies ready for implementation in thermal manufacturing industries, as well as high-priority areas for development.

Advanced thermal technologies have the potential to improve efficiency, productivity, and global competitiveness for a wide range of thermal manufacturing processes. These methods rely on heat-driven techniques such as drying, smelting, heat treating, curing, and forming. Thermal manufacturing is estimated to directly and indirectly affect the employment of over 5 million people in the U.S. in more than 100,000 establishments.

Previous efforts to identify and pursue these technology advancements have occurred independently from one another (e.g., Heat Treating Technology Roadmap). However, a number of key technologies and process improvements are widely applicable to the many industries that comprise the broad thermal manufacturing community.

To help move this project forward, TMI ATC compiled a review of state-of-the-art thermal manufacturing with the aim of developing a foundation for the needs and opportunities related to advanced thermal manufacturing technologies across relevant industries and involving all key stakeholders. Consortium project managers reviewed previous industry roadmaps to identify critical needs and opportunities in thermal manufacturing, interviewed nearly two dozen experts in the thermal manufacturing community, and searched websites of relevant organizations to provide an overview of recent and current work related to thermal manufacturing.

These efforts resulted in identifying the most important needs and opportunities as well as recent efforts being conducted in several areas including:

- Modeling and Simulation
- Sensors
- Heat Generation Methods
- Process Intensification
- Energy and Emissions Reduction
- Automation and Robotics
- Advanced Materials

Developing and implementing these technologies in parallel will provide optimum value. Read the complete review by visiting the TMI ATC website at asminternational.org/web/tmi-atc/home under Resource Library and then State of the Art.

*Stan Theobald*
Senior Director,
Business Development
ASM International

## Petrus Inducted as ASM Fellow

**Gregory J. Petrus**, president, Forged Right First LLC, Hinckley, Ohio, was inducted as an ASM Fellow at the MS&T14 Awards Ceremony on October 14 in Pittsburgh. He is recognized "for significant contributions to physical metallurgy through development of innovative solutions using simulation tools for enhancing metalworking and heat treating to exploit a wide array of materials structure/property/processing relationships."

*Gregory Petrus (left) accepts his ASM Fellow citation from ASM President Ravi Ravindran, FASM.*

## 2014 ASM HTS/Bodycote Best Paper in Heat Treating Awarded

*Anthony Lombardi (left), Ph.D. candidate in mechanical engineering at Ryerson University and winner of the 2014 HTS/Bodycote Best Paper in Heat Treating Award, is congratulated by ASM President Ravi Ravindran, FASM, at the ASM Leadership Awards Luncheon on October 13, 2014, during MS&T in Pittsburgh. Lombardi's paper is entitled "Development of Methodology to Improve Mechanical Properties of 319 Al Alloy Engine Blocks through Cost-Effective Heat Treatment Optimization."*

## Connelly is 2014 Recipient of the George A. Roberts Award

*Michael B. Connelly (right), vice president, Casey Products, Woodridge, Ill., accepts the 2014 George A. Roberts Award from Amy Ebeling, granddaughter of George A. Roberts. Connelly is one of the founding volunteers of the ASM Materials Camp program and participated in the Eisenman Camp for 15 years. He also participated in the start-up of the Materials Explorer's Camp in France and served on the ASM Materials Education Foundation Board.*

# First ASM HTS/Surface Combustion Emerging Leader Award to Be Presented in 2015

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.

**Nominations must be submitted to ASM Headquarters no later than April 1, 2015.**

For rules and nomination form for the ASM HTS/Surface Combustion Emerging Leader Award, visit the Heat Treating Society Community Website at http://hts.asminternational.org and click on Membership & Networking and HT Awards.

For additional information, or to submit a nomination, contact Joanne Miller at 440.338.5151, ext. 5513, joanne.miller@asminternational.org.

# Soliciting 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 also is open to those students who have graduated within the past three years and whose paper describes work completed while an undergraduate or post graduate student. The winner receives a plaque and check for $2500.

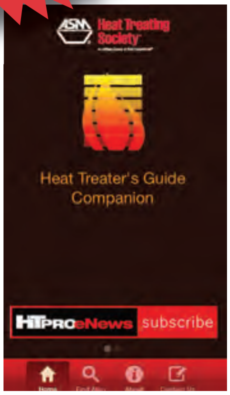
To view rules for eligibility and paper submission, visit the Heat Treating Society website at http://hts.asminternational.org/portal/site/hts/HTS_Awards.

**Paper submission deadline is December 12, 2014**. Submissions should be sent to Joanne Miller, ASM Heat Treating Society, 9639 Kinsman Rd., Materials Park, OH 44073, 440.338.5151 ext. 5513, joanne.miller@asminternational.org.

# Heat Treating App Update Released by ASM Heat Treating Society

Available for iPhone, iPad and Android

ASM International and the ASM Heat Treating Society released Version 2 of the free mobile app, the *Heat Treater's Guide Companion*. Version 2 provides ready reference data on more than 330 steel alloys, nearly doubling the number of alloys in the previous release. In addition to carbon and alloy steels, the app now includes stainless steels, tool steels, and ultrahigh-strength steels, and also features enhanced searching.




Content includes chemical composition, similar steels, characteristics, and recommended heat treating practices. The app can be used by itself or as a companion to the ASM *Heat Treater's Guide* print and online database products, which provide additional heat treating data such as representative photomicrographs, isothermal transformation diagrams, cooling transformation diagrams, tempering curves, and data on dimensional change.

*Heat Treater's Guide Companion,* Version 2 is available in the Apple and Google App Stores. 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, a Vice President, a Student Board Member, 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 April 1, 2015**.

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 Joanne Miller at 440.338.5151 ext. 5513, joanne.miller@asminternational.org.

CALL FOR PAPERS

ASM HEAT TREATING SOCIETY 2015 CONFERENCE & EXPOSITION

## HT 2015 – 28th ASM Heat Treating Society Conference and Exposition
## October 20–22, 2015
## Cobo Convention Center, Detroit

The ASM Heat Treating Society and the American Gear Manufacturers Association are co-locating to provide an exciting mix of education, technology, networking, and exposition opportunities at the 28th Heat Treating Conference and Exposition and Gear Expo, the premier heat treating gathering in North America. The event will offer a full technical program covering a broad scope of heat treating technology, networking opportunities, and a first-hand look at equipment, supplies, and services from exhibitors.

HTS 2015 organizers are seeking original, previously unpublished, noncommercial papers for oral and poster presentations.

**Abstract submission deadline: January 26, 2015.** Visit the HTS website at http://hts.asminternational.org for details on suggested program topics and submitting an abstract, and click on Events tab.

## Heat Treating Society Looking for Volunteers

The HTS Board is seeking enthusiastic, committed members to serve on various HTS Committees that monitor technical advances and other areas of member interest to bring new information to members through products and services. HTS members are requested to consider serving on one of the following committees:

- Awards and Nominating Committee
- Education Committee
- Technology & Programming Committee
- Exposition Committee
- Finance Committee
- Membership Committee
- Research and Development Committee

Interested members should review the Committee Purpose on the HTS website at http://hts.asminternational.org and contact joanne.miller@asminternational.org.

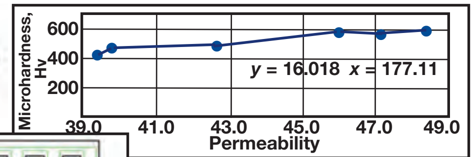
## CORRECTION

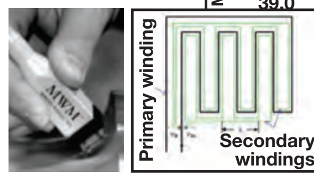
In the September 2014 issue of *HTPro* in *AM&P* (p 58), the photo of the vacuum furnace hot zone should have been credited to Solar Atmospheres, Souderton, Pa. We apologize for any inconvenience this may have caused.

# Breakthroughs in Nondestructive Measuring Techniques

WPI Center for Heat Treating Excellence

The Center for Heat Treating Excellence (CHTE) at Worcester Polytechnic Institute (WPI) in Massachusetts is conducting a cutting-edge research project aimed at measuring the surface hardness and case depth on carburized steels for process verification and control. The results will enable companies to improve the quality of heat-treated products faster and more cost-effectively.



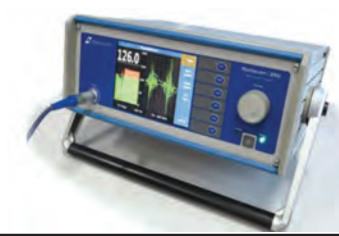




*Meandering winding magnetometer (MWM) used to measure surface hardness. At a high frequency (5 MHz), permeability measured by the MWM sensor has good correlation with surface hardness.*

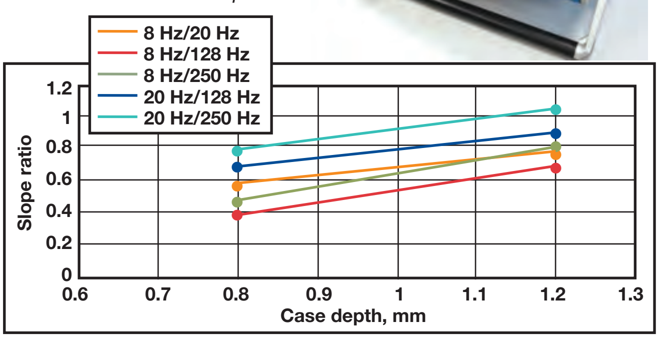
"This is the first time a project like this is being undertaken," explains Lei Zhang, CHTE researcher and Ph.D. candidate at WPI. "Our focus is on developing new measurement techniques that will enhance product quality."

According to lead researcher Richard Sisson, Jr., George F. Fuller Professor of Mechanical Engineering at WPI, and CHTE director, the heat treating industry needs rapid, accurate nondestructive techniques to measure surface hardness and case depth on carburized steels for process verification and control. "Current measurement methods require destructive testing with traveler specimens that cannot always represent the configurations of the production part, nor the associated subtleties of thermal history, carbon atmosphere, and geometry influenced diffusion. Our research will eliminate much of the guesswork."

Another industry challenge with the traveler specimen-measurement method is that it often requires periodic sectioning of production parts to validate the hardness and case depth after carburization, especially for critical shaft and gear teeth configurations. "This method is labor intensive, expensive, and susceptible to operator error, as well as counterintuitive to the end result of high quality, usable heat-treated parts," explains Sisson.




*Barkhausen noise unit used to measure case depth. The magnetization voltage sweep method has been applied, and the slope ratio reflects the case depth variation of the tested part.*




A key challenge of the project is to distinguish between hardness and residual stress, because most techniques currently used to measure case depth are not only sensitive to hardness distribution, but also to residual stress distribution.

Nondestructive techniques being evaluated initially include eddy current, meandering winding magnetometer (MWM), Barkhausen noise testing, and alternating current potential drop.

The project focuses on four tasks:

- Identify nondestructive techniques to measure surface hardness and case depth and develop a fundamental understanding of their mechanisms. Select nondestructive techniques for testing based on project objective and equipment availability.
- Select alloys and design heat treating conditions to be used to create testing standards using the simulation method, and fabricate and characterize the standards.
- Conduct nondestructive tests to determine the correlations between the destructive test results and the known results in the standard.
- Determine correlations among nondestructive test measurements, hardness, and microstructure for the standards. Verify the effectiveness of the respective nondestructive test technique in industry.

Completion of the research project is expected in 2016.

**About CHTE**

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

**Member research process**

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

CHTE also periodically undertakes large-scale projects funded by the federal government or foundations. These endeavors keep members informed about leading edge technology.

**CHTE current research portfolio**

Other projects now in progress include:

- Improving Alloy Furnace Hardware Life
- Induction Tempering
- Gas Quench Steel Hardenability
- Cold Spray Nanomaterials (supported by ARL)

For more information about CHTE, its research projects, and member services, visit wpi.edu/+chte, call 508.831.5592, or email Rick Sisson at sisson@wpi.edu, or Diran Apelian at dapelian@wpi.edu.

# DEEP CASE BORIDING FOR EXTREME WEAR RESISTANCE

THE ABILITY TO PRODUCE DEEPER CASE BORIDE LAYERS THAT ARE NOT PRONE TO SPALLING MAKES THE BORIDING PROCESS COMPETITIVE WITH SOME CONVENTIONAL DEEP-CASE AND THICK-COATING PROCESSES.

Craig Zimmerman* and Nick Bugliarello-Wondrich,* Bluewater Thermal Solutions

Boriding (also known as boronizing) is a diffusion-based case-hardening process for metals that creates an ultrahigh hardness case (1500–2200 HV) below the surface of the parts being treated. It produces exceptional wear resistance for metal parts that operate in severely abrasive and erosive operating conditions and also improves anti-galling properties. Boriding typically more than triples the service life of high wear parts compared with other traditional heat treatments such as carburizing, carbonitriding, nitriding, nitrocarburizing, thin PVD coatings, and platings like hard chrome. Boriding creates a wear layer with higher hardness than many wear resistant thermal spray coatings, such as tungsten carbide and chrome carbide. It is not mechanically bonded to the surface, but instead is diffused below the surface of the metal, making it less prone to peeling and breaking off treated parts.

Boriding is performed by diffusing boron atoms into a metal surface and allowing the boron to react with elements present in the substrate to form metal-boride compounds. Upon diffusing enough boron into the surface, a metal-boride compound layer with high hardness precipitates and grows below the surface of the part. Different types of metal-boride layers are possible, the composition of which depends on the material being treated. For example, iron-boride layers form in steels and cast irons and nickel-boride layers form in nickel-base alloys. Other compounds possible include cobalt and titanium borides. This article discusses only boriding of ferrous alloys.

Two iron-boride compounds formed when boriding steel are $Fe_2B$ (at lower boron concentrations) and FeB (at higher boron concentrations), each having different structures, densities, and mechanical properties as shown in Table 1[1].

*Member of ASM Heat Treating Society

**TABLE 1 — PROPERTIES AND CHARACTERISTICS OF IRON-BORIDE COMPOUNDS**

| | FeB | $Fe_2B$ |
|---|---|---|
| Boron content, wt% | 16.23 | 8.83 |
| Structure | Rhombic | Tetragonal |
| Residual stress on cooling | Tensile | Compressive |
| Coefficient of linear thermal expansion, $\times 10^{-6}$/K | 23 | 7.9–9.2 |
| Hardness (HV0.1) | 1900–2100 | 1800–2000 |
| Density, g/cm$^3$ (lb/in.$^3$) | 6.75 (0.244) | 7.43 (0.268) |

*Single-phase $Fe_2B$ layers.* As boron diffuses into a steel surface, concentration at the surface starts out at zero and begins to increase until the concentration just below the surface reaches a level where $Fe_2B$ compounds begin to precipitate and grow. $Fe_2B$ is the first phase to form, as it contains a lower boron concentration (33%) than FeB, which requires 50% boron concentration. A solid continuous single-phase $Fe_2B$ layer forms below the surface and grows deeper over time as boron concentration increases. An $Fe_2B$ single-phase layer is the ideal result and is the desired microstructure after boriding ferrous materials.

*Dual-phase $Fe_2B$-FeB layers.* Boriding the part for longer times to create a deeper case makes it more likely the boron concentration just below the surface will exceed 33%, which leads to the formation of the more boron-rich FeB compound in addition to the already formed $Fe_2B$.

Powder pack cementation is the most commonly used method for boriding. A drawback of the process is that the boron activity of the powder pack is fixed; it cannot be varied during the process. This makes it impossible to perform a diffusion process similar to the boost-diffuse methods used in carburizing and two-stage Floe nitriding. In these processes, carbon and nitrogen potentials of the furnace atmosphere can be reduced to lower values during later stages of the process to avoid oversaturating the surface with excessive carbon or nitrogen, which are responsible for carbide networking, excessive retained austenite, and/or nitride networking. Therefore, boriding to deeper case depths with a fixed high boron activity during the entire process eventually oversaturates the surface with boron, forming a second FeB layer on the outside of the original $Fe_2B$ layer.

Most commercially available boriding powders create high boron activity levels, and are good for quickly forming high-quality thin boride layers with short cycle times. However, there is a limit to the depth of the single-phase layer that can be formed with longer cycle times before undesirable FeB begins to precipitate resulting in a dual-phase FeB-$Fe_2B$ layer. The limit on depth depends on the material as each one has a different boron diffusivity rate.

Plain carbon and lower alloy steels generally have higher boron diffusivity rates and enable rapid diffusion to deeper depths without a buildup of high boron concentration at the surface. More highly alloyed steels have lower boron diffusivity rates, which tends to trap boron near the surface. This increases surface boron concentration, forming

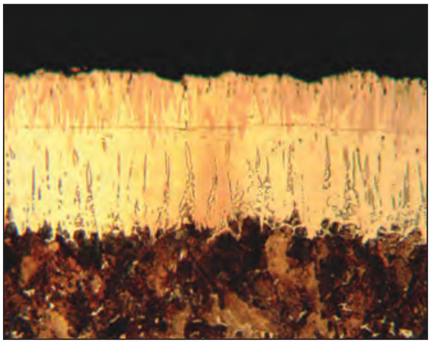


**Fig. 1 —** *Dual-phase boride layer with FeB (darker "teeth" near surface) and $Fe_2B$ (lighter teeth). Cracks have formed between the FeB and $Fe_2B$ layers upon cooling.*

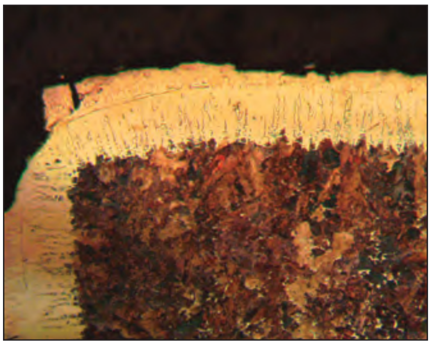


**Fig. 2 —** *Dual-phase boride layer with cracks between the FeB and $Fe_2B$ layers. The FeB boride layer at the corner spalled off the surface.*

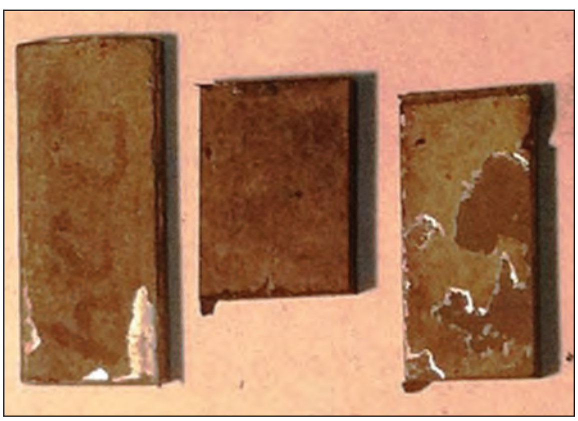


**Fig. 3 —** *Spalling (small silver-colored relective spots) on three different materials that were borided together: (left) 304 stainless steel, (center) 440C stainless steel, and (right) duplex stainless steel.*

dual-phase FeB-$Fe_2B$ layers earlier in the cycle at shallower boride layer depths. For example, 1018 plain carbon steel can be boronized to about 0.004 in. deep using commercially available Ekabor 1 boriding powders before any FeB begins to form. A higher alloy 4140 steel can only be borided to about 0.003 in. deep before FeB begins to form using the same boriding agent. Materials having even higher alloy content, such as Types 304, 440, and 17-4 stainless steels, form FeB at depths less than 0.001 in. Thus, plain carbon steels are attractive candidate materials for boriding, as they can be borided deeper while still maintaining a single phase $Fe_2B$ layer. They also are less expensive than higher alloy steels.

Dual-phase boride layers are undesirable compared with an $F_2B$ single-phase layer. The main problem with dual phase layers is that their coefficients of thermal expansion and densities differ with respect to one another. The boride layers are formed at relatively high temperatures (1550°–1750°F) and these layers contract at different rates when cooled to ambient temperature, generating stresses between them. The $Fe_2B$ layer on the steel substrate is in a state of compressive residual stress (desirable) and the FeB layer on the surface of the $Fe_2B$ layer is in a state of tensile stress. This can cause cracks to form between the layers, and the FeB layer often spalls off the surface during cooling. Figure 1 shows a dual-phase boride layer consisting of $Fe_2B$ (lighter colored deep "teeth") and FeB (darker colored shallow teeth) near the surface. Stress-related cracks in the dual-phase layer run parallel to the material's surface. Cracking is even more prevalent in borided parts having outside corners and edges where surface boron concentration is high due to simultaneous boron diffusion into the surface from multiple angles. Figure 2 shows an example of spalling at the corner of a borided part where cracks formed between the FeB and $Fe_2B$ layers, resulting in the FeB layer spalling off at the corner. If spalling does not occur immediately during cooling, residual tensile stresses in the FeB layer make it very easy to chip and break during handling and in the field. Spalled areas appear as small silver-colored reflective spots (Fig. 3).

## Deep case boriding

Historically, information on boriding in the literature states that boriding deeper than 0.005 in. is not recommended on many materials due to dual-layer formation, which is prone to spalling and fracture of the layer. However, many design engineers want to form deeper boride layers to provide longer wear life. Recognizing this need, Bluewater Thermal Solutions developed new deep-case boriding processes for several different material grades. While the use of high temperatures and longer cycle times enables this, the challenge is to create deeper layers while maintaining a single-phase $Fe_2B$ layer. Figure 4 shows an example of borided 4140 alloy steel using standard commercially available boriding powders to a layer depth of 0.020 in. Nearly one half of the total boride layer depth is FeB, which is not a desirable structure.

Deep boriding with a single-phase $Fe_2B$ layer in concept is simply to prevent boron concentration at the surface from rising to a level where FeB begins to form while allowing boron to continue to diffuse deeper. However, the powder pack process makes this difficult due to a fixed boron activity level. There are a number of alternative approaches to accomplish deep boriding with a single-phase $Fe_2B$ layer:

(1). The boriding process can be carried out at a high boron potential, then cool the parts to ambient temperature, remove them from the powder pack, and reheat in a protective inert atmosphere with no boron present to allow further boron diffusion, while reducing the surface boron concentration. A limitation of this approach is spalling of the boride layer during cooling. In many cases, boride layers spall off part surfaces immediately as they are removed from the boriding process. It is also difficult to predict what post-boriding diffusion cycles are necessary to reduce surface boron concentrations to a level where all the FeB borides are dissolved and reduced back into a single-phase $Fe_2B$ boride layer.

Figure 5 shows an example of deep-case borided 4140 alloy steel with FeB present at the surface after boriding. The material was reheated in an inert atmosphere to diffuse away FeB that formed at the surface. However, the diffusion treatment on the piece was insufficient to reduce all of the FeB present. The near surface has fully reverted from FeB (darker teeth) into $Fe_2B$ (lighter teeth), but there is still some FeB present at depths between 0.001 and 0.002 in. that was not converted into $Fe_2B$. It is crucial in this process to ensure that spalling does not occur between the boost and diffuse steps and that the diffuse process is sufficient to ensure that all FeB is reduced into $Fe_2B$ by the end of the process.

(2). The entire boriding process can be carried out at lower boron potentials so FeB never forms. This requires the development of a customized boriding powder different from most of the standard commercially available boriding powders. With many different boron sources, activators, and diluents available to choose from, a wide array of different results are possible through the development of customized boriding powders. However, each grade of material will boride differently as they all have different boron diffusivity rates necessitating a different customized powder for each material. Another drawback of boriding at lower boron potentials is that the boron enters the parts very slowly, requiring longer cycle times. Substantial knowledge, testing, experimentation, and research are required to develop customized deep-case boriding powders for different materials and desired boride layer depths.

(3). A method where a boost-diffuse type process comparable to gas carburizing and gas nitriding, such as electrolytic salt-bath boriding, could be used. The method involves immersing parts into a borax salt bath held at austenitizing temperatures. Parts are connected to a dc power supply (cathodes) and graphite plates are connected to the powder supply and immersed into the salt bath (anodes). Boriding occurs as electric current flows through the system with borax reacting with both parts and anodes to free up boron atoms that diffuse into the part surfaces. The boost-diffuse process is possible because boriding only occurs as electric current is applied. When current is off, boron continues to diffuse into the parts at austenitizing temperature. Thus, a deeper boride layer forms while reducing the boron concentration at the surface of the parts. The process, called phase homogenization in electrochemical boriding (PHEB), was developed by G. Kartal, S. Timur, V. Sista, O.L. Eryilmaz, and A. Erdemir[2].

The process has not yet gained widespread industrial acceptance due to various problems such as salt residues being difficult to remove from parts, difficulties in building and maintaining a borax salt-bath furnace, and questions about reliability and safety of high electrical current flowing through a high-temperature borax salt bath. Another concern is the ability to maintain uniform electrical connectivity of the parts to the fixtures as the fixture material degrades.

(4). Another boost-diffuse boriding process could use boriding gases in an atmosphere furnace for a portion of a cycle and then replace the boriding gases with an inert gas, or adjust the gases to reduce the boriding potential during later stages of the process. Bluewater Thermal Solutions is developing this type of process, but details are proprietary and are not discussed at length here.

## Results of deep-case boriding

Bluewater Thermal Solutions has developed several deep-case boriding processes, which are currently being performed commercially. Parts treated using these processes outperform conventionally borided parts with shallower boride layers in several applications including oilfield drilling equipment, industrial pumps, high wear agricultural machinery parts, and ground-engaging tools, all subject to harsh abrasive and erosive wear conditions.

Materials including 1018 plain carbon steel, 4140 alloy steel, and O1, A2, D2, and S7 tool steels have been deep case borided with a single-phase $Fe_2B$ layer with no spalling problems. Steels like 1018 and 4140, traditionally borided to a depth of 0.003 to 0.005 in., are now able to be deep case borided to a depth of 0.010 to 0.020 in. Tool steels like O1, A2, and S7, traditionally borided to a depth of 0.001 to 0.003 in., can be deep case borided to a depth of 0.008 to 0.012 in. Martensitic and PH grade stainless steels, traditionally borided to a depth of 0.001 in., can be borided to a depth of 0.004 in. with no spalling problems. Figure 6 shows a photomicrograph of 4140 alloy steel deep case borided to a depth of 0.015 in. where the structure is predom-

**Fig. 4 —** *AISI 4140 alloy steel deep case borided to a depth of 0.020 in. using commercially available boriding powder. The boride layer consists of about 50% FeB (dark colored teeth near surface) and 50% $Fe_2B$ (lighter teeth) below the FeB layer, an undesirable condition prone to spalling.*

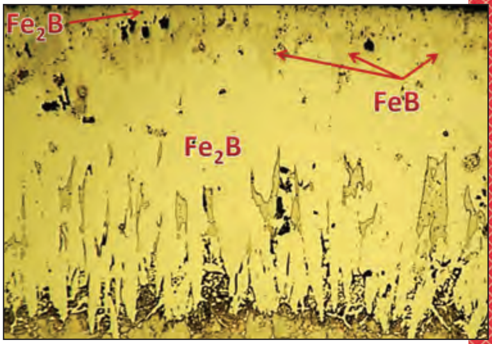



**Fig. 5 —** *AISI 4140 alloy steel deep case borided to a depth of 0.011 in. followed by a vacuum diffusion treatment. Some FeB near the surface converted back to single-phase $Fe_2B$ (light colored teeth) while some FeB (darker teeth) is still present at slightly deeper depths. Single-phase $Fe_2B$ is present below.*

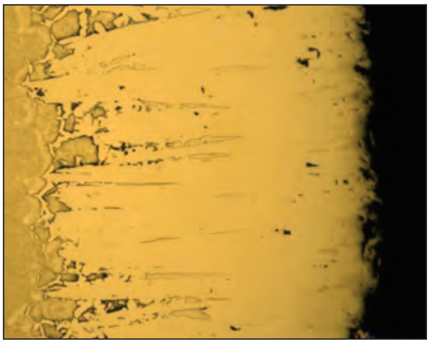


**Fig. 6 —** *AISI 4140 alloy steel deep case borided to a depth of 0.015 in. consisting of nearly 100% single-phase $Fe_2B$ with only minor traces of FeB (darker colored teeth) near the surface.*

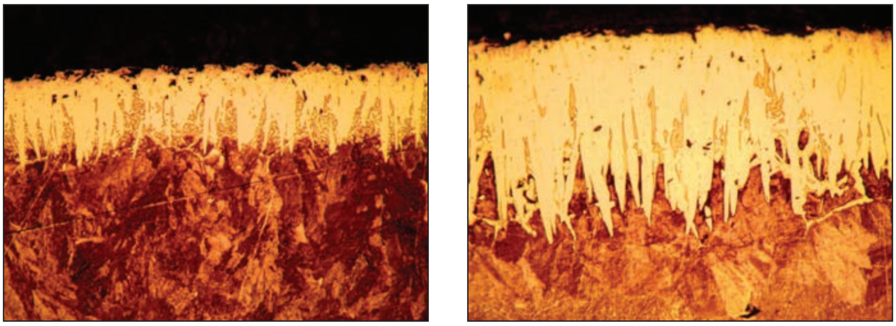


**Fig. 7 —** *AISI 4140 alloy steel ground-engaging tools conventionally borided to a depth of 0.004 in. (left) and deep case borided to a depth of 0.010 in. (right). Boride layers in both are single-phase $Fe_2B$.*

**Fig. 8 —** *AISI 1045 plain carbon steel high-wear agricultural machinery parts borided to a depth of 0.005 in. (left) and deep case borided to a depth of 0.014 in. (right). After service on the same machine for the same amount of time, the conventional borided part shows significant material loss due to wear, while the deep case borided part shows virtually no wear.*

inately $Fe_2B$ with only minor traces of FeB present at the surface.

To design a process capable of creating a specific boride layer depth comprising single-phase $Fe_2B$, each steel grade requires different processing parameters in terms of cycle time, temperature, and boron potential for each stage of the process. For instance, processing parameters used for deep case boriding 1018 plain carbon steel are quite different than the parameters for A2 tool steel to produce a 0.015 in. deep single-phase $Fe_2B$ layer.

## Applications and performance

Deep case boriding of parts provides greater depth of the ultrahigh hardness boride layer, which extends the wear life of parts. For example, a ground-engaging tool manufactured with a carbide wear insert is now being borided with improved wear life. Two sets of the tool were provided to a manufacturer for field testing to compare service life-to-failure of tools treated with a conventional 0.004 in. boride layer depth and a deep case borided 0.010 in. layer depth. Figure 7 shows the microstructures of each tool set. After multiple field trials, the manufacturer of these tools elected to have the deep boriding process specified for its tools, even at a higher cost than the conventional boriding process or tools made with a carbide insert. According to the manufacturer, the 0.010 in. boride depth versus the 0.004 in. boride depth is 75 to 100% more durable under varying soil conditions. The relative wear properties of the parts with deeper boride treatment are superior in a cost-benefit analysis.

An oilfield drilling-tool company is specifying the deep boriding process for its tools, which are exposed to high pressure flow of abrasive particles. Deep boriding improved tool performance to the point of lasting for the entire well-drilling process compared with previous parts that wore out and failed during drilling, requiring costly downtime to replace the tools.

Bluewater provided two sets each of a conventionally borided and deep case borided high-wear part to an agricultural machinery manufacturer to compare wear performance in abrasive crop and soil conditions. Conventional boriding more than doubled the expected life of these parts over heat treating alone. At the point where the conventional boride layer wore off, the deep case borided parts still had quite a bit of boride layer depth present and did not show much signs of wear. Figure 8 shows the wear surface of the two components where the shallow borided part shows significant material loss while the deep borided component shows very little material loss due to wear.

Bluewater Thermal Solutions' custom designed deep-boriding processes were successful for each project. The ability to customize the process for different steel grades and application requirements can make boriding a more popular choice to treat parts exposed to harsh wear environments. Deep case boriding enables producing wear layer depths comparable to competitive processes such as carburizing, nitriding, thermal spray coatings, and hardfacing. In addition to having a comparable wear-resistant depth, boride layers are much harder than carburized and nitrided cases, and have similar or higher hardness than many flame spray and hardface coatings, while maintaining better dimensional tolerances than the coating processes, which add material. Deep case boriding could be the solution to wear problems in many applications where parts are exposed to extreme wear in harsh operating environments. **HTPRO**

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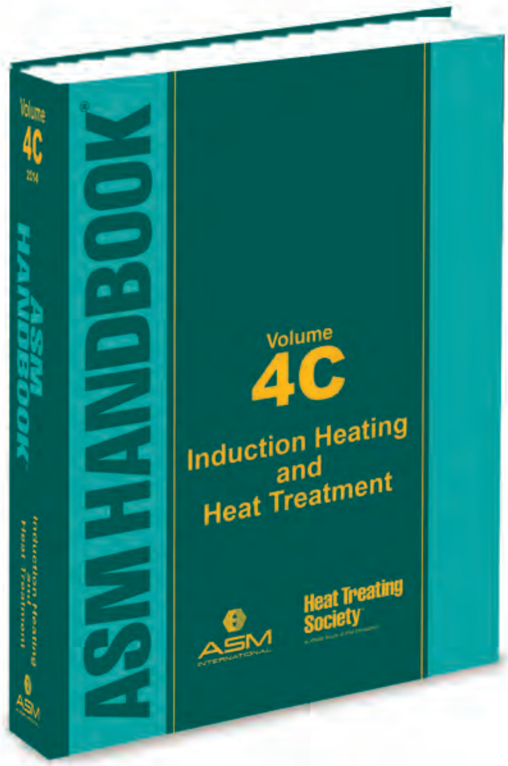
# NEW TECHNICAL RESOURCE FOR INDUCTION HEATING PROFESSIONALS

THE RECENTLY PUBLISHED *INDUCTION HEATING AND HEAT TREATMENT*, VOL 4C, *ASM HANDBOOK*, IS THE RESULT OF AN AMBITIOUS UNDERTAKING TO COMPILE AN ALL-NEW, COMPREHENSIVE RESOURCE ON INDUCTION THERMAL PROCESSES.

**Dr. Valery Rudnev,* FASM,** Inductoheat Inc.




Heating by means of electromagnetic induction is a topic of major significance, and the technology continues to grow at an accelerated rate. Thermal applications include hardening, tempering, stress relieving, brazing, soldering, melting, normalizing, annealing, and coating, as well as reheating ferrous and nonferrous metallic materials prior to warm and hot working. The recently published *Induction Heating and Heat Treatment*, Vol 4C, *ASM Handbook*, is the result of an ambitious undertaking to compile an all-new, comprehensive resource on induction thermal processes to meet the needs of the induction heating and heat treating communities.

Continuing in the tradition of the *ASM Handbook* series, Vol 4C combines practical knowledge in ready-to-use diagrams, technical procedures, guidelines, know-how, and good practices with up-to-date knowledge emphasizing the specifics of induction processes compared with alternative technologies. Common misconceptions, erroneous assumptions, and misleading postulations are clarified and explained using easy-to-understand computer modeling charts, practical data, and numerous case studies.

This technical resource provides a practical, comprehensive reference on the technologies and applications of induction heating and heat treatment. It is written for design, manufacturing, and materials engineers. Internationally recognized experts from leading universities, research laboratories, and industrial corporations from 10 countries contributed to this handbook.

Following is a brief glimpse of the breadth of content in Volume 4C, which begins with a review of electrical, electromagnetic, heat transfer, and material science fundamentals related to induction heating. Other critical facets associated with induction heating technologies are also discussed, such as the nonequilibrium nature of phase transformations and other metallurgical subtleties related to the specifics of induction hardening, tempering, and stress relieving. Attention is given to the effect of prior microstructure on the selection of required temperatures and process parameters, and guidelines are presented that reflect the differences in stel response to the short heating times.

Subtleties of induction hardening of critical components such as shafts, gears, axle shafts, camshafts, crankshafts, and other components used in automotive and off-road machinery, aeronautic and aerospace, farming, appliance, and oil and gas industries are also covered. Several articles introduce novel technologies and know-how that enable minimizing part distortion dramatically after heat treating, which potentially could lead to elimination of secondary operations such as straightening. For example, regardless of the complexity of camshaft geometry, shape of lobes (Fig. 1), and positioning, novel induction hardening techniques often make it possible to obtain accurate contour hardness patterns. This produces uniform fine-grain martensitic surface layers and almost undetectable distortion (Fig. 2), which, in turn, improves overall process cost-effectiveness, energy efficiency, and quality of heat treated components[1].

A critical review of ASTM and SAE

**Fig. 1 —** *Automotive cam lobe shape varies depending on engine design. Courtesy of Inductoheat Inc.*

**Fig. 2 —** *True contour hardening of camshaft lobes. Courtesy of Inductoheat Inc.*

**Member of ASM International and Heat Treating Society*

standards and guidelines for properly measuring hardness of the case and heat affected zone, as well as a review of issues and complications related to different hardness measuring techniques are also included. Case studies of pattern specifications are presented, and special attention is given to proper monitoring of induction processes, destructive and nondestructive testing, and quality assurance.

The new handbook also includes in-depth analysis of ways to develop robust, efficient, and high-quality processes; the formation of initial, transient, and residual stresses and their effect on the performance of heat treated components, shape distortion, and cracking potential. Studies have been conducted to evaluate stress formation during heating and spray quenching in workpieces with classical shapes and parts with geometrical irregularities such as fillets, diameter changes, and holes. For example, Figs. 3 and 4 show finite-element mesh with nodal locations in the proximity of an oil-hole and the variation of maximum principal stress during spray quenching, respectively[2]. A quench delay has a significant effect on the appearance of transient and residual stresses.

Selection of critical process parameters and review of inductor designs, heat pattern control, intricacies in using magnetic flux concentrators, and spray quench design considerations are included as well.

Another topic area covers subtleties in determining temperature requirements when induction heating plain carbon and alloy steels, superalloys, titanium, aluminum and copper alloys, and other materials prior to hot and warm working. Novel technological developments in heating billets, bars, tubes, rods, and other metallic workpieces, as well as a concept for controlling a billet's true temperature are discussed.

Development of optimization procedures, principles of multiobjective optimization, and strategies for obtaining optimal process control algorithms based on various technological criteria, real-life constraints, and cost functions (e.g., maximizing throughput, temperature uniformity, energy effectiveness, minimizing required shop floor space, metal loss, etc. is also explored.).

Failure analysis and prevention, which are associated with product quality, process cost-effectiveness, downtime losses, and other issues are discussed as well. Many publications covering failure analysis are devoted primarily to heat treating processes other than induction, therefore several articles in this handbook discuss various aspects of failure analysis of components heat treated using electromagnetic induction. Typical defects, abnormal characteristics, and root causes of different failures are discussed, as well as the effects of metallurgical factors and abnormalities such as excessive grain coarsening, presence of decarburized layers, inclusions, seams, laps, mixed structures, and overheated and burned steels. Causes of surface, transverse, and longitudinal internal cracks and their prevention are reviewed.

The new volume also includes good practices in designing and fabricating long-lasting inductors and ways to avoid their premature failures. A fishbone diagram of premature failure

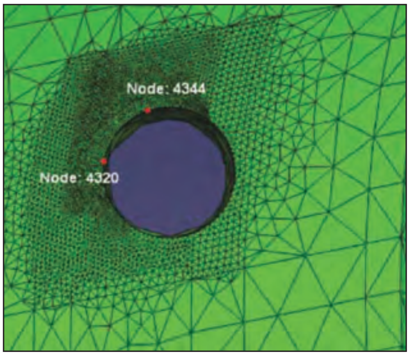



**Fig. 3 —** *Nodal locations on oil-hole edge of crankshaft bearing section.*

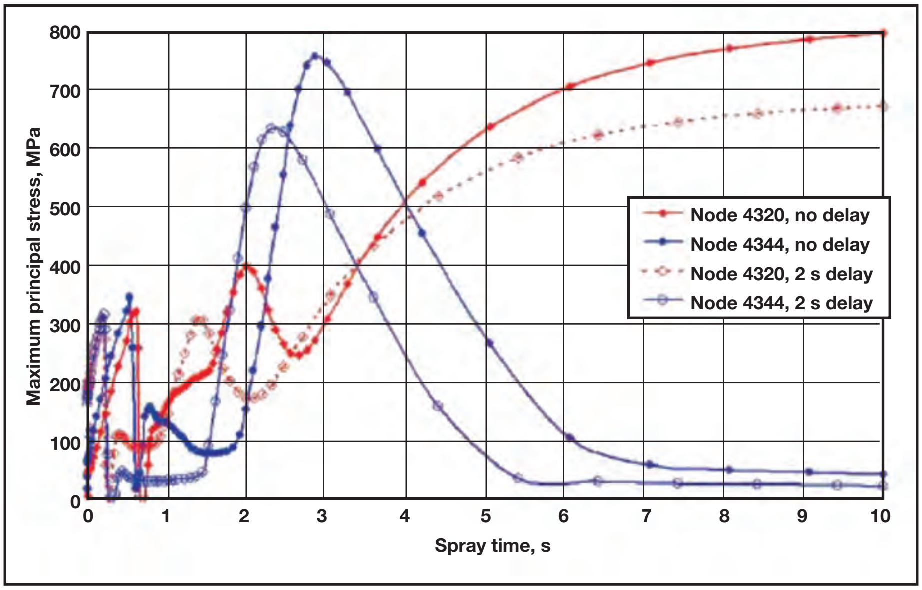



**Fig. 4 —** *Maximum principal stress at node locations in Fig. 3 as a function of spray quench time.*

of induction coils serves as a guide in determining potential root cause(s) of premature coil failures.

Special applications of electromagnetic induction, including melting of glasses and oxides, optical fiber drawing, nanoparticle heating, and hyperthermia applications are also discussed.

Design principles and operation specifics of modern transistor and thyristor power supplies used for induction heating are described using conventional and advanced circuits. An appreciable amount of material is devoted to practical aspects, including review of transformer designs and load-matching facets and standard and customized induction equipment.

Volume 4C also contains numerous case studies that illustrate the challenges and solutions in obtaining required thermal conditions for a workpiece, as well as the subtleties of computer modeling of induction thermal processes.

Special attention is given to describing the aspects of process monitoring, maintenance, and water cooling, as well as safety procedures, energy efficiency, and environmental factors including control of electromagnetic field (EMF) exposure. EMF is invisible and is associated with the operation of any electrical device. Several international organizations raised concerns related to external EMF exposure, developing awareness regarding nonionizing radiation, and the evaluation of health risks associated with EMF exposure. These organizations include:

- The World Health Organization (WHO)
- The Institute of Electrical and Electronic Engineers (IEEE)
- The U.S. Occupational Safety & Health Administration (OSHA)
- The International Radiation Protection Association (IRPA)

Studies were conducted to evaluate direct and indirect effects of EMF exposure on health, passive and active medical implants, hypersensitivity, etc., leading to the creation of a number of international standards, guidelines, and regulations. Being unaware of basic principles related to electromagnetic field exposure and unfamiliar with the results of studies conducted by various professional societies and international health organizations can result in incorrect assumptions. One article in this handbook aims to clarify this subject by reviewing key concepts regarding occupational exposure to electromagnetic fields encountered in industrial activities with which professionals should be aware, measures used to evaluate these situations, and rules and international standards applicable to a 50 Hz to 10 MHz frequency range[3].

## Summary

This reference provides practitioners, students, engineers, and scientists with the knowledge to better understand the various interrelated physical phenomena of induction heating and heat treating. Much of the content in the 62 articles in this handbook has not been published before. To provide a snapshot of the wealth of information contained in Vol 4C, a series of brief articles highlighting some of material in different chapters are now being published in subsequent issues of *HTPro*. The review articles are authored by Valery Rudnev (Professor Induction), who together with George Totten served as co-editors of the handbook. **HTPRO**

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