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Thermal processing

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2022 is going to be a great year (fingers crossed)

2020 wasn't the greatest of years, and 2021 seemed to be a year that kept trying to outdo it at every turn. Thankfully, that didn't happen — for the most part.

On a positive note, with the country and the world still on the mend, it looks like the heat-treating industry is showing every sign of snapping back from a crippling pandemic.

But as we enter 2022 and beyond, let this note not only serve as a season's greeting, but also as a promise that *Thermal Processing* will continue to explore ways to enhance our products with the ultimate goal of getting the best and latest information about the heat-treating industry in your hands — whether that be virtually or literally — just as we did this year and in many years' past.

But before we say a final goodbye to 2021, make sure you take some time to discover this month's issue of *Thermal Processing*, which contains quite a bit of information.

December's topics are gear applications as well as metrology and inspection.

With that in mind, our cover article is a fascinating article from AFC-Holcroft President and CEO Bill Disler on the benefits of close interaction between gear designers and heat-treat specialists and how it can lead to total cost and quality optimization.

Our next article presents a new framework based on the ridge Mamdani fuzzy logic system for the mapping of process features to areal surface metrology parameters.

Our third feature is of particular interest to me. At the recent Motion+Power Technology Expo, I had the opportunity to see a panel discussion on women in manufacturing. I thought it was such a fascinating subject that I contacted the women on the panel to further discuss the opportunities, challenges, and myths that surround the roles of women who are in the manufacturing field and the ones who may one day enter it. It was a pleasure to talk to them about their experiences and their advice. Please check it out, and if you're a company that's looking for diversity, consider expanding your hiring field. It might turn out to be one of the best decisions you'll ever make.

You'll find that and much more in our December issue. And keep in mind that we are always looking for interesting and educational editorial content, so if you have a technical paper or other heat-treat-related articles you'd like to see published, please contact me. I'd love to hear from you and be given the opportunity to share your unique knowledge with our readers.

Happy holidays from all of us at *Thermal Processing*. Stay safe, and, as always, thanks for reading!

KENNETH CARTER, EDITOR
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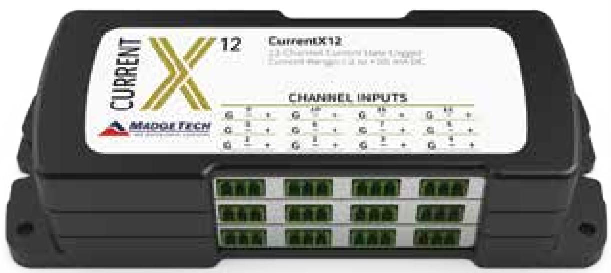

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Inspired by the shapes, strength, and thinness of everyday objects such as tin cans, Behnisch Architekten worked with Josef Gartner GmbH/Permasteelisa North America Corp. and the German fabricator Edelstahl-Mechanik to create the world's first hydroformed tensile façade. (Courtesy: Photo by Brad Feinknopf)

Bodycote heat treats sun shading for new Harvard complex

German fabricator Edelstahl-Mechanik, supported by Bodycote, a global thermal processing services company, manufactured the world's first hydroformed tensile architectural façade. Designed by Behnisch Architekten, the newly constructed Science and Engineering Complex at the Harvard University campus in Boston, Massachusetts, is an example of balancing sustainability and aesthetic goals.

A total of 12,800 steel panels in 14 different profiles were precisely fabricated and sculpted using hydroforming by fabricator Edelstahl-Mechanik. Commonly used within the automotive and aerospace industries, hydroforming uses water pressure to shape thin metal plates against a mold, creating custom pieces. The stainless-steel panels were then annealed (a heat-treatment process that alters the microstructure of a material to change its mechanical or electrical properties) by Bodycote.

In keeping with the university's dedication to sustainability, exterior stainless-steel façade panels were designed to minimize solar heat gain in warm weather months, capture thermal energy in cold weather months, and provide natural light to the interior spaces. Stainless steel can be used in all aspects of architecture, building, and construction and is widely used due to its attractive appearance, corrosion resistance, strength, ease of maintenance, low life cycle costs, and lightweight properties.

Bodycote Group Chief Executive Stephen Harris said, "We are very pleased to have contributed to this project where sustainability has been at the forefront in all design aspects. The project demonstrates the value of how our thermal processing solutions can be applied to not only aerospace or automotive industries, but for architectural applications providing durable and sustainable solutions."

MORE INFO www.bodycote.com

Plibrico targets aluminum processors with new refractory

The Plibrico Company, a leading supplier of monolithic refractories and construction services, introduced Plicast Al-Rezist™, a line of low-cement, aluminum-resistant refractories expressly engineered to mitigate damaging and costly corundum growth in furnaces.

For aluminum processors, one of the costliest operational challenges in high production environments is the aggressive formation of corundum deposits in furnaces. Excessive, damaging, and costly, corundum growth can be mitigated with the right refractory materials, coupled with proper maintenance. Plibrico's Plicast Al-Rezist line of refractory materials is engineered for processors who run their aluminum melting and holding furnaces hotter and faster for extended periods of time, and therefore require superior aluminum-resistant refractory performance.

"Due to robust demand, processors, foundries, and die casters are operating furnaces at or above maximum production rates, leading to one of the industry's most costly operational challenges: preventing corundum growth that will destroy a refractory lining," said Brad Taylor, president and CEO of the Plibrico Company. "We introduced Plicast Al-Rezist to meet today's need for a more resistant, longer lasting refractory that protects our clients' furnaces from corundum and other destructive forces."

Plicast Al-Rezist is strongly recommended for protection of the furnace hearth, lower sidewall, and belly bands. These areas of metal contact suffer the most mechanical abuse and metal penetration. The Plicast Al-Rezist line is produced with an enhanced multi-component package for exceptional performance against more aggressive

SEND US YOUR NEWS Companies wishing to submit materials for inclusion in Thermal Processing's Update section should contact the editor, Kenneth Carter, at editor@thermalprocessing.com. Releases accompanied by color images will be given first consideration.

Plibrico's Plicast Al-Rezist™ protects in extreme environments and mitigates costly corundum growth. (Courtesy: Plibrico)

alloys, including those with high fluidity. This multi-component system prevents aluminum from wetting the surface of the refractory and growing corundum below the surface line. In fact, in multiple blind tests, Plicast Al-Rezist had an unmeasurable amount of aluminum penetration, while other brands had 0.15" amount of penetration. As a result of this formula, the material exhibits excellent physical properties for demanding service conditions so repairs and downtime are kept to an absolute minimum. That is one of the reasons it is rated "Excellent" by the industry standard ALCOA® Refractory Evaluation Parameters.

Developed with installation in mind, Plicast Al-Rezist is simple to apply with flexible options including Cast, Pump, or VibCast. It is also ideal for use in precast shapes since its rheology enables smooth crisp shape lines and corners.

Engineered to resist corundum growth, thermal shock, and abrasion in extreme aluminum processing environments, Plibrico's Al-Rezist line of castables offers superior aluminum penetration resistance and refractory performance, extending the life of the furnace, maximizing production uptime, and keeping downtime and repairs to a minimum.

MORE INFO www.plibrico.com

International Thermal Systems moves to new facility

International Thermal Systems (ITS) has moved into a new, more expansive and modern facility only eight miles from its previous location.

The new facility will allow ITS to meet its goals for continued growth by providing additional, upgraded space for developing precise heat-processing and aqueous-washing solutions for a broad array of industries, including automotive, aerospace, power generation, battery manufacturing, building products, foundry, and metal packaging industries.

"This new, modern location is another milestone in the long, successful history of ITS. It is a key part of our plan to keep growing and improving our business. In this new location, we will continue to provide our customers exactly the solutions they expect and rely upon us to deliver," said Tom Stricker, president, ITS. "We are very excited to highlight all of our capabilities in this new space and to continue to bring fresh, new talent into our organization."

MORE INFO www.internationalthermalsystems.com

JetFirst 100-200 Bench-top RTP system. (Courtesy: ECM-USA)

ECM finds market success for rapid thermal processing

ECM's product expansion with research and development and laboratory furnace systems, brand name JIPELEC, has proven highly successful within the academic and semiconductor industries.

With the recent increased interest in U.S. semiconductor research and manufacturing, ECM is excited to announce a strong bimonthly sales order pattern for 2021. These smaller-scale system processes range from rapid thermal processing (RTP), annealing (RTA), oxidation (RTO), nitridation (RTN), diffusion (RTD) to sulfurization, selenization, and crystallization. Of the several orders placed so far in 2021, the bench-top JIPELEC JetFirst 100-200 product line leads the way as a cold-wall, single-wafer RTP furnace for process engineering and qualification using atmospheric or vacuum thermal treatment.

JIPELEC JetFirst systems are compact and robust halogen lamp heated rapid thermal processing systems specifically designed to meet the requirements of research and small-scale production units with substrate size ranging from pieces of sample to 300-millimeter diameter. In general, RTP is a flexible technology that provides fast heating and cooling to process temperatures of ~200-1,300°C with ramp rates typically 20-200°C/sec, combined with excellent gas ambient control which allows for the creation of sophisticated multi-stage processes within one processing recipe. The full range of JIPELEC RTP/RTA furnace systems cover all research, lab, and clean environment applications, and can be manually operated or integrated within a fully automated system designed and maintained by the ECM Robotics division.

MORE INFO www.ecm-usa.com

Don Hendry takes gavel as 2022 MTI president

One area of strength for the Metal Treating Institute over the years has been its line of leadership, and 2022 is no different. At the awards dinner during MTI's October Fall Meeting in San Antonio, Texas, 2021 president Jim Oakes from Super Systems passed the gavel to the new 2022 president, Don Hendry from Pinson Valley Heat Treating out of Pinson, Alabama.

With Pinson Valley Heat Treating as a member since 1988, Hendry brings a wealth of knowledge, vision, and history to the table as president. Hendry is a third-generation heat treater with his grandfather starting the business in 1970. This is his second stint on the MTI Board of Trustees. During Hendry's first tenure, he was very active on the MTI safety committee. Hendry was elected again in 2014 to MTI's Board and has played a major role in MTI's growth since rejoining the Board.

Don Hendry

MTI announced the new slate of 2022 officers, as well as two newly elected Board Members for three-year terms:

The 2022 officers are:

» **President:** Don Hendry, Pinson Valley Heat Treating, Pinson, Alabama.

» **President-elect:** Jim Orr, Penna Flame Industries, Zelienople, Pennsylvania.

» **Treasurer:** Glen Ottinger, Thermo-Fusion, Hayward, California.

» **Immediate past president:** Jim Oakes, Super Systems, Cincinnati, Ohio.

The Metal Treating Institute (MTI) is a non-profit trade association representing the largest network of commercial heat treaters in the world and the suppliers who support them. MTI's mission is to help heat treaters succeed through information and business programs focused on quality, audit compliance, safety, industry forecasting, technical training and leadership development.

MORE INFO www.heattreat.net

Kolene Corp. grows in heat-treat market with acquisition

Kolene Corporation, a global leader of custom-designed and engineered molten salt bath equipment and specialty chemical formulations, acquired Upton Industries in Roseville, Michigan.

"Kolene has always looked for ways to grow revenues, both organically through our R&D efforts and externally by acquisition. When the opportunity presented itself to begin discussions with Upton, the similarities between the two companies and what we provide to the customers in the industries that we serve, made this marriage ideal," said Roger L. Shoemaker, chairman & CEO of Kolene. "We are proud to carry on Upton's strong brand and legacy as a part of Kolene Corporation as we move forward."

Founded in 1937, Upton Industries are experts in the design and manufacture of thermal processing systems in the metal heat-treating industry. Upton's engineered thermal-solutions methodology has allowed the company to become a leader in traditional lines of heat-treat equipment including box type, car bottom, lift-off, and specialty furnaces using either electric heating or gas-fired systems. Kolene will maintain both the Detroit headquarters location and the Roseville location, which will be home to all Kolene's manufacturing and fabrication. By bringing the two companies together, the new Kolene will house nearly 50,000 square feet of manufacturing, fabrication, and commercial processing capabilities.

W. Scott Schilling, Kolene president, said, "After thoroughly evaluating Upton's capabilities, it was apparent that there are tremendous synergies between the two companies. Capitalizing on these synergies will allow Kolene to expand into applications and revenue segments where we have not historically been. Kolene will also have the ability to become more vertically integrated due to Upton's manufacturing and fabrications capabilities, which will allow us to strengthen our overall margins. The two companies are a perfect fit."

In its 82nd year, Detroit-based Kolene Corporation provides custom-designed and engineered equipment, specialized chemical formulations, and processes for cleaning and conditioning metal surfaces. Kolene's products are used worldwide for casting cleaning, alloy descaling, coatings removal, engine rebuild, and other demanding automotive, industrial, and military applications.

MORE INFO www.kolene.com

Nitrex featured on CBS News' 'Global Thought Leaders'

Nitrex Metal Inc., provider of fully integrated surface-treatment solutions and technologies, has been selected for the Global Thought Leaders series broadcast on CBS News. The feature showcases the company as an industry innovator whose surface-treatment solutions enhance the metallurgical properties of components increasing their durability, wear, and corrosion resistance while contributing to a more sustainable future.

"We are pleased to be chosen by CBS News to demonstrate how Nitrex's technologies and innovations make our customers' products achieve superior quality results," said Jean-François Cloutier, CEO of Nitrex.

A partner with several global companies in the aerospace, automotive, industrial, and renewable energy sectors, Nitrex has been at the forefront of some of the most advanced surface-treatment solutions that increasingly meet stringent requirements for nearly 40 years. Nitrex's revolutionary nitriding process, most reliable vacuum furnaces, services centers, proprietary software, and controls make Nitrex the only fully integrated solutions provider in the surface-treatment industry.

"Our commitment to continuous innovation has allowed us to help our customers bring more value, better performance, and greater reliability and predictability to manufactured parts while operating in a greener way," Cloutier said. "As the manufacturing industry continues to innovate and thrive, Nitrex will continue to help our customers build products that are stronger for longer than others dare to dream."

Nitrex is the first company to offer a fully automated software-controlled nitriding/nitrocarburizing system, allowing customers to achieve precise and repeatable quality.

MORE INFO www.nitrex.com

Bodycote increases hot isostatic pressing capacity in the U.S.

Bodycote, the world's largest thermal processing services provider, is expanding its hot isostatic pressing (HIP) capability in Greenville, South Carolina, United States.

The new HIP capacity, which will be online in the first half of 2022, will focus on developments in additive manufacturing and advanced materials. The two additional vessels further extend the company's comprehensive range of installed capacity across the world. Bodycote's Greenville site is a Nadcap accredited site and holds several core OEM approvals. The site consists of numerous vacuum furnaces and other capabilities well suited to supporting additive manufacturing customers. The Greenville site will serve the aerospace, defense, medical, and general industrial customers throughout the Southeastern region.

"We are pleased to address our customer needs by bringing HIP services closer to their facilities. With the largest HIP operational capacity in the world, our continued investment demonstrates Bodycote's commitment to align resources to serve our customers across North America," said Stephen Harris, Bodycote Group chief executive.

Bodycote operates the world's largest network of HIP equipment. Having established industry expertise over decades, Bodycote has more than 50 HIP vessels of varying sizes in multiple locations.

MORE INFO www.bodycote.com

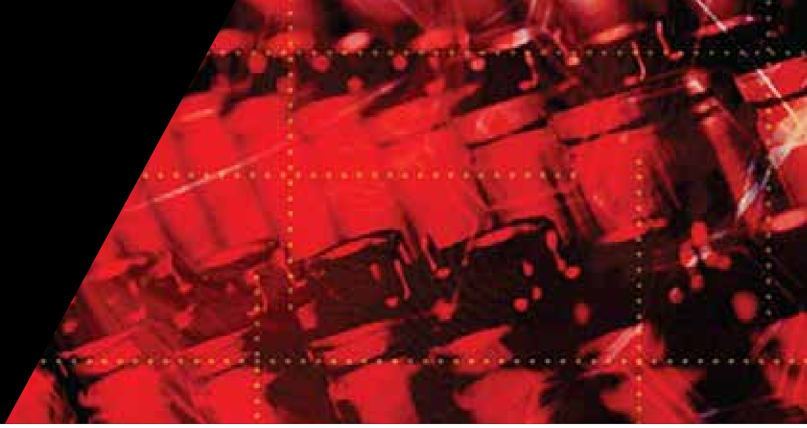
Ed Engelhard recognized with MTI industry merit award

Ed Engelhard received the MTI Award of Industry Merit. (Courtesy: Solar Atmospheres)

As long-time members of the Metal Treating Institute (MTI), Solar Atmospheres employees are actively involved with the Institute. At the recent 2021 Fall meeting held in San Antonio Texas, MTI recognized Ed Engelhard, vice president corporate quality, with the MTI Award of Industry Merit. This award is given in recognition of current/ongoing commitment to the betterment of the commercial heat-treating industry with one or more significant accomplishments.

Engelhard co-chairs the Technical Standards Committee for the MTI. Additionally, he is extremely active with PRI, SAE, and at ASTM. Bob Hill, President of Solar Atmospheres of Western PA, said, "Being a previous business owner coupled with 40 years of metallurgical processing knowledge, Ed knows what it takes to get the job done and to get it finished right the first time. He has the unique ability to separate the utopian desires of auditing agencies versus what is practical on the shop floors because he has been there. We are extremely proud that the MTI honored Ed for openly sharing his knowledge to our heat-treating industry."

MORE INFO www.solaratm.com



27th IFHTSE Congress, European conference on heat treatment headed to Austria

The special emphasis of ECHT2022 will be on Heat Treatment in Steel Processing. Topics include furnace design, thermomechanical treatments, quenching technology, additive manufacturing, and coating technologies.

The 27th IFHTSE Congress will be in Salzburg, Austria, September 5-8, 2022 at the Wyndham Grand Salzburg Conference Center. The conference chairs are Eva Troell, RISE IVF Research Institutes of Sweden (Sweden and present President of IFHTSE); Masahiro Okumiya, Toyota Technological Institute (Japan and upcoming president of IFHTSE); and Reinhold Schneider, University of Applied Sciences Upper Austria (Austria) and chairman of the ASMET Heat Treatment Committee.

This conference will also celebrate the 50th anniversary of IFHTSE.

IMPORTANT DATES

- **Abstract submission deadline:** January 31, 2022.
- **Notification of acceptance:** March 31, 2022.
- **Preliminary program:** April 30, 2022.
- **Full paper submission deadline:** May 31, 2022.

Please submit your abstracts (300-400 words) via the conference website: www.ifhtse-echt2022.org.

The special emphasis of ECHT2022 will be on Heat Treatment in Steel Processing. Topics include furnace design, thermomechanical treatments, quenching technology, additive manufacturing, and coating technologies.

12TH TOOLING 2022 CONFERENCE AND EXHIBITION

The Tooling conferences have been held since 1987 and come alternately with IFHTSE's "International Conference on Heat Treatment and Surface Engineering of Tools and Dies (HTSE-TD)," which was last held online January by our Chinese member association CHTA. While HTSE-TD focuses on HTSE, the "Tooling" conferences cover the entire field: All kinds of tool steels, hard metals and cermets, simulations and modeling, the entire chain of all processing technologies, performance, microstructure/properties, wear resistance, fatigue (mechanical and thermal), and corrosion resistance are to be discussed. For more information, go to: www.tooling2022.org.

5TH INTERNATIONAL CONFERENCE ON HEAT TREATMENT AND SURFACE ENGINEERING OF TOOLS AND DIES

The 5th International Conference on Heat Treatment and Surface Engineering of Tools and Dies will be April 21-24, 2023, in Liangzhu Dream Town, Hangzhou, China. This event is organized by the Chinese Heat Treating Association. After the fourth event of the series held in online format in January 2021, with 10,000-plus individual visits, it is hoped that international experts in the field can meet in person. The conference focuses on the exchange of ideas and to promote the application of advanced heat treatment, surface engineering technologies, and equipment for tools and dies. The goal is improving the reliability and service life of tools and dies and realizing progress in strengthening basic disciplines. More information will be forthcoming regarding this event. Contact email is chta@chta.org.cn.

IFHTSE GLOSSARY

At the present time, the IFHTSE is creating a multi-language glossary. While the basis for the glossary will be based on ISO 4885, the list of terms is insufficient and lacking in many surface engineering technology terms. The goal is to produce a glossary, including definitions. The definitions will be provided in English. The initial goal is to host the glossary on the IFHTSE website.

SPOTLIGHT ON MEMBERS

IFHTSE is a federation of organizations, not individuals. There are three groups of members: scientific or technical societies and associations; universities and registered research institutes; and companies.

In this segment, we will highlight our members. This month we highlight Associazione Italiana Di Metallurgia, the metallurgical society of Italy. This society was founded in January 1946 as a "non-profit, cultural society whose objective is the dissemination of science and technology related to metals and other materials for engineering." It is currently its 75th anniversary.

The scope of the association is to foster, through its activities, the exchange of ideas and experiences among those who are interested in the development and progress of the metallic material field with particular emphasis in the promotion of meetings for producers, users, and researchers.

The AIM publication program covers a wide range of subjects from physical metallurgy to production processes of metals and their applications. AIM publishes technical-scientific books, proceedings of major events organized by AIM, the scientific journal "La Metallurgia Italiana," and a series of reference manuals produced for AIM courses and workshops.

AIM is the "home" association of IFHTSE Vice President (from January 2022) Prof. Massimo Pellizzari of the University of Trento.

The current President is Ing. Federico Mazzolari - Gruppo Arvedi. For more information, go to www.metallurgia-italiana.net/eng.

IFHTSE 2022 EVENTS

APRIL 25–27, 2022
12th Tooling Conference & Exhibition (Tooling 2022)
Örebro, Sweden I www.tooling2022.org

JUNE 19–23, 2022
6th International Conference on Steels in Cars and Trucks
Salzburg, Austria I www.sct-2020.com

SEPTEMBER 5–8, 2022
27th IFHTSE Congress / European Conference on Heat Treatment
Salzburg, Austria I www.ifhtseecht2022.org

APRIL 21–24, 2023
5th International Conference on Heat Treatment and Surface Engineering of Tools and Dies
Liangzhu Dream Town, Hangzhou, China

MAY 2023
European Conference on Heat Treatment
Italy

NOVEMBER 13-16, 2023
28th IFHTSE Congress
Yokohama, Japan

For details on IFHTSE events, go to www.ifhtse.org/events

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Fundamentals of Industrial Process Heating – learn online with IHEA

The curriculum includes the basics of heat transfer, fuels and combustion, energy use, furnace design, refractories, automatic control, and atmospheres as applied to industrial process heating.

IHEA's Fundamentals of Industrial Process Heating Online Learning Course has been a successful source of high-level learning to those in the industrial heat processing industry for more than 10 years. Registration for the 2022 winter course is now open, and, for the past few years, the course has sold out, so early registration is encouraged. Scheduled to begin January 17, the six-week class will run through February 27. The flexible online format and interactive forums with other students, along with scheduled office hours with the instructor, are just a few of the benefits of this program.

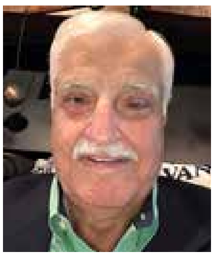
The course is ideal for students to learn in a virtual format while at home or in the office. It is affordable and allows students to go at their own pace. The course offers indispensable tools to industrial process heating operators and users of all types of industrial heating equipment. Throughout the in-depth online course, students learn safe, efficient operation of industrial heating equipment, how to reduce energy consumption, and ways to improve the bottom line. The course content provides an excellent overview of the essential areas used throughout the industry.

The curriculum includes the basics of heat transfer, fuels and combustion, energy use, furnace design, refractories, automatic control, and atmospheres as applied to industrial process heating. Weekly coursework, quizzes, and a final exam project are administered to guide students on their progress and evaluate their knowledge of the material. For a complete listing of the topics covered, visit www.

ihea.org/event/OnlineWinter21.

This online course is a terrific value for IHEA members and non-members alike, considering no travel expenses are involved, and there is no time out of the office.

This course is designed to give the student a fundamental understanding of the mechanisms of heat transfer within an industrial furnace and the associated losses and the operation of a heating source either as fuel combustion or electricity. All concepts are derived mathematically with limited use of "rules of thumb." As one of the prime objectives, the student will learn how to properly size the heating system to accomplish the required furnace output. Radiant heat transfer, in particular, is a very complex phenomenon requiring rigorous mathematical analysis. It is rarely addressed at the undergraduate level; therefore, the student should have a solid basis in undergraduate thermodynamics for this course.


Jack Marino

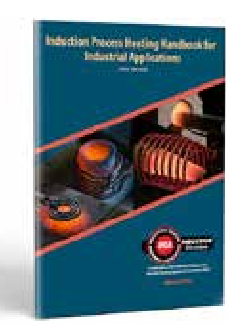
A former online student said, "Because of balancing an extremely busy workload and family life, I am not able to be on a regular schedule or take time in the evening to travel to a class. The advantage for me is that I can check in when time permits and still stay current on all activities. The course information is directly related to my work, and I found it to be very beneficial."

Industry expert Jack Marino will lead students in this six-week online course. Marino, a registered professional engineer with more than 40 years' experience in the heat processing business, is a graduate of Rensselaer Polytechnic Institute with a bachelor's degree in aeronautical engineering and holds a master's degree in engineering science from Penn State. His knowledge and experience offer invaluable resources that online students can access throughout the course.

Registration for the Fundamentals course is open now through January 14, 2022, at www.ihea.org/event/OnlineWinter21. Cost for IHEA members is $750 or one member voucher, and cost for non-members is $925. Registration fee includes an electronic course handbook, course instruction, quizzes and projects, class forums, and the opportunity to contact the instructor throughout the course. Students who successfully complete the course will receive 18 PDHs. Printed materials are available for an additional fee.

IHEA'S NEW PUBLICATION AVAILABLE

The Industrial Heating Equipment Association's (IHEA) Induction Division recently published the *Induction Process Heating Handbook for Industrial Applications – First Edition*. The publication is now available for purchase on the IHEA website. Induction Division members collaborated for several months to compile the content and provide a comprehensive handbook on induction hearing.



The handbook is a quick introduction to basic operations and the many applications of induction heating in industrial processes. The basic principles of induction heating have been understood and applied to manufacturing since the 1920s. During World War II, the technology developed rapidly to meet urgent wartime requirements for a fast, reliable process to harden metal engine parts. Since that time, the applications for induction heating have extended to many manufacturing processes including pre- and post-heat treating, surface hardening, forging, sealing, bonding, annealing, and welding, among others.

"Following the lead of IHEA's long-standing Infrared Division (IRED), the Induction Division of IHEA has developed the *Induction Process Heating Handbook for Industrial Applications, First Edition*," said Induction committee chair Michael Stowe. "By no means a textbook, this handbook will provide basic information on how induction works and the equipment and operation for induction processes. Additionally, and perhaps the most valuable, is a wide range of induction heating applications and examples. For someone interested in induction heating as a possible technology for new or retrofit processes, this handbook is a great place to start."

Special thanks to the contributing companies for their hard work and diligent efforts that went into creating this new handbook: Advanced Energy; Alabama Power, a Southern Company; Ambrell; Dry Coolers, Inc.; and Electric Power Research Institute (EPRI).

The new *Induction Process Heating Handbook for Industrial Applications – First Edition* is now available in the IHEA bookstore, www.ihea.org/store. The cost is $20 for members and $40 for non-members.

JUSTIN SIMS
MECHANICAL ENGINEER /// DANTE SOLUTIONS

Heat treatment simulation can aid in the design of better press quench tooling.

Press quenching tooling design using simulation

Steel powertrain gears are commonly carburized and quench hardened to improve strength and wear characteristics. However, solid-state phase changes occurring within the steel during the hardening process can introduce large distortion. To control the distortion of complex gear designs, press quenching is often used in industry. [1] Press quenching is a process that uses specially designed tooling and a press machine to help control the distortion of complex geometries being quench hardened. The press unit is fitted with oil channels to direct cooling fluid at the part. It should also be noted that the goal of press quenching is not to "hold" the part in place but to encourage deformation of the component in a controlled and predictable manner.

A previous Metal Urgency column, "Modeling Can Improve Press Quenching Process," [2] discussed using the heat-treatment simulation software DANTE to evaluate a press-quenching process of a straight bevel gear experiencing radial distortion issues of its bore. [3,4] The previous article explored modifying the press quench tooling to improve the radial distortion response, with the main focus being on the bore of the gear and the improvement gained from replacing the expander used to control the bore dimension with a solid plug. However, the astute reader would have noticed the gap between the gear and the "lower outer die," as shown at A in Figure 1 (upper left). The defined gap is not an arbitrary choice, and the gap distance will have a significant effect on the bevel distortion.

The plot in Figure 1 (lower), axial displacement of point B versus time, shows the effect the lower die can have on the bevel distortion during the process. The load on the "upper outer die" pushes the bevel down while the component is in the austenite phase and holds it against the "lower outer die." As the austenite is transformed to martensite, the expansion to martensite causes the bevel to separate from the "lower outer die," and nearly return to its original position (zero on the plot).

While this may seem easy enough, the design of the bevel support, labeled "lower outer die" in Figure 1, is not a trivial activity. There are three major parameters associated with designing the bevel support: the load placed on the "upper outer die," the radial location of the support under the bevel, and the gap between the bevel and the "lower outer die." All of these parameters significantly affect the final deflection of the bevel gear tip at the outer diameter and the overall bow of the tooth. These two distortion modes are described by Figure 2. The deflection is determined by subtracting the vertical

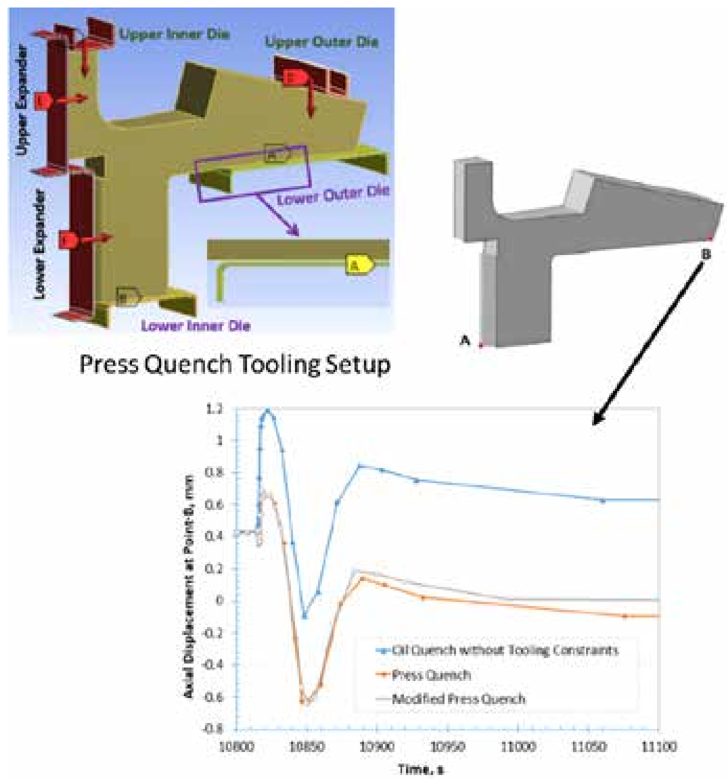


Figure 1: Gear geometry and press quench tooling modeled in the previous Metal Urgency column (upper left); single tooth CAD model of previously modeled gear showing locations of line plots (upper right); and line plot of axial displacement vs. time for three conditions evaluated in the previous article that show the influence of the lower die under the bevel (lower).

displacement at point C (the free end of the beam) in Figure 2 from the vertical displacement at point A; point A is fixed, so the displacement is always zero at point A. The overall bow is determined by subtracting point C from point B. It should be noted that point C is generally at the free end of the beam, but the location of point B will vary depending on the values of the major parameters previously mentioned, as will be shown.

To explore the effects of these parameters on the two critical distortion modes, a simplified model was constructed to mimic the bevel teeth of a bevel gear. The first simplification was to assume

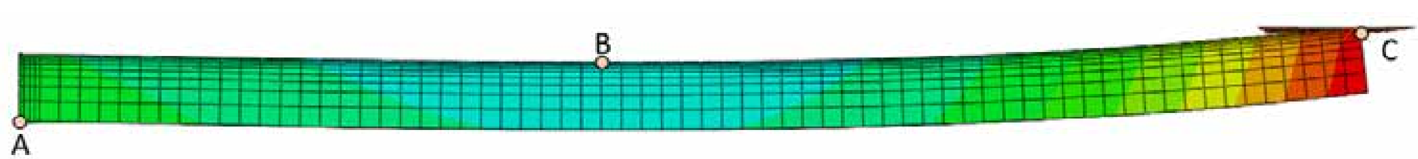


Figure 2: Beam showing distortion modes of a bevel gear tooth.

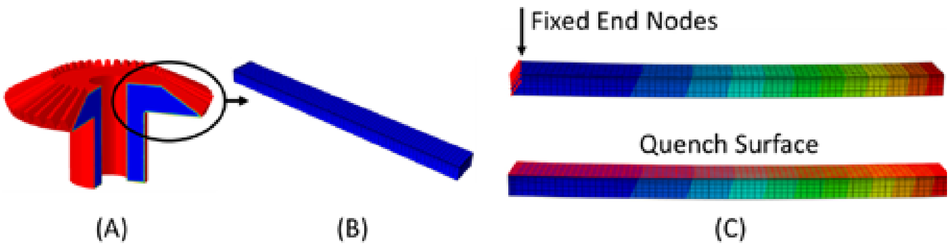


Figure 3: (A) 270° section of original CAD geometry; (B) fixed location of simplified model; and (C) quenched surface of simplified model.

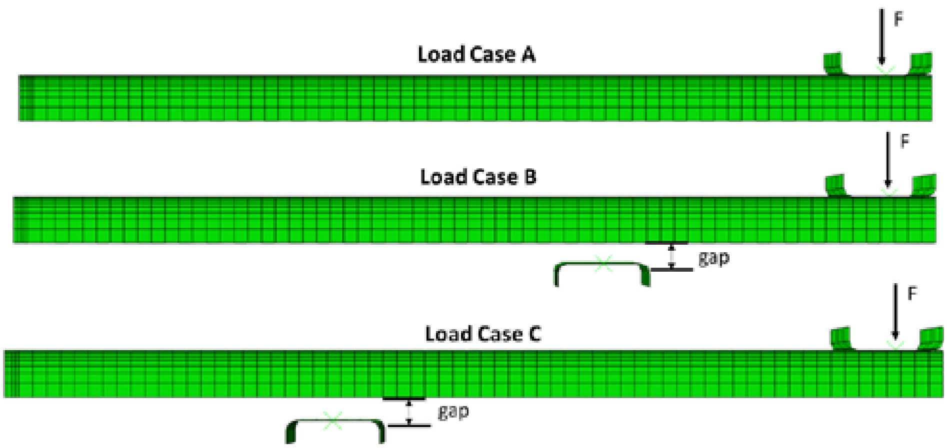


Figure 4: Load cases evaluated for this study.

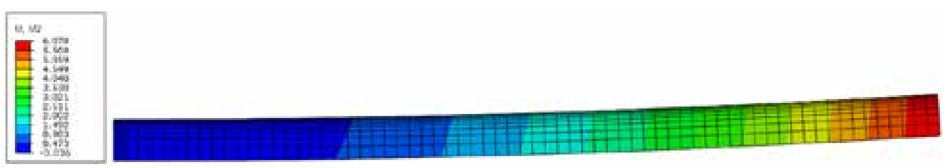


Figure 5: Axial distortion prediction of beam subjected to no constraints during quenching.

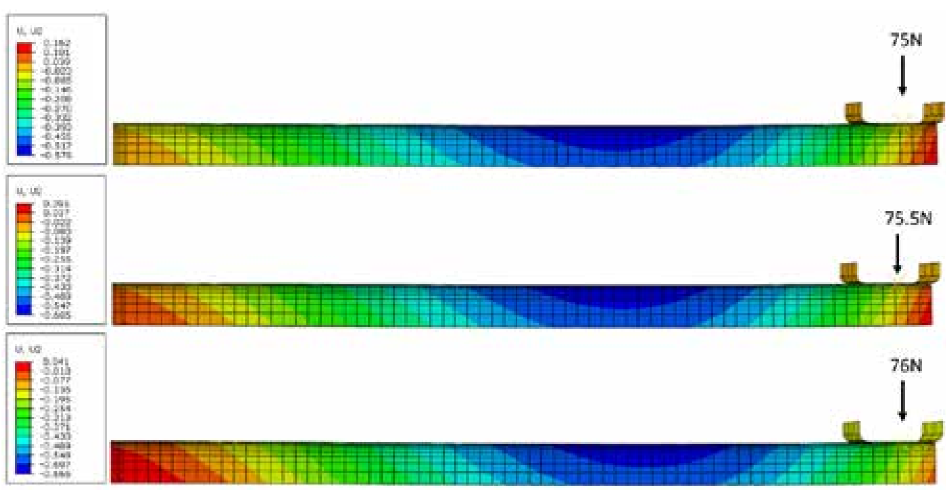


Figure 6: Axial distortion prediction for Load Case A with minor loading differences.

the bevel teeth behaved as a cantilever beam. Figure 3A shows a 270° section of the original CAD geometry and Figure 3B shows the cantilever beam used for this study. It was also assumed that one end of the beam was completely fixed, as it is attached to the gear hub, and only the top surface was quenched, to mimic the increased cooling rate provided by the additional surface area of the gear teeth. This is shown in Figure 3C.

In the design of actual equipment, the gear geometry being processed should be modeled. However, the simplifications made here can provide insight into how these three parameters interact to manipulate the final distortion of the component after a press-quenching process. Simplifications such as this can also be made in the initial design iterations to quickly gain an understanding for how certain load and die configurations affect distortion. The accuracy of this simplification can be improved upon if the beam's stiffness is equivalent to the gear tooth's stiffness.

Figure 4 shows the three loading cases examined: Load Case A applies a load to the free end of the beam, by means of an upper die, with no lower die. The force was varied to evaluate distortion of the beam from this configuration. A zero-load condition was also executed for Load Case A to evaluate the distortion if the beam was quenched without tooling constraints. It is always good practice to evaluate the geometry without constraints to ascertain how the geometry wants to naturally deform, prior to any attempt at designing the tooling configuration and loading scheme. Load Case B applies the load to the free end of the beam also but uses a lower die approximately 1/3 distance from the free end. The load and lower die gap were varied to evaluate the effects on distortion. Load Case C also uses an end load and lower die, but the lower die is approximately 2/3 distance from the free end. The load and lower die gap were varied to evaluate the effects on distortion from this loading configuration.

To begin the study, a model was executed that placed no constraints on the geometry. This condition should always be evaluated first to determine natural distortion modes induced by the geometry and the cooling conditions. Figure 5 shows the results of the free quench, no constraints model. The results show a tip deflection of 6 mm, with a bow of approximately the same amount. Incremental loads were subsequently placed on the outer die of Load Case A until the beam straightness became optimized. A load of 75.5 N was found to offer the best results, with respect to minimum tip deflection and overall straightness. Figure 6 shows how sensitive the distortion can be for geometries such as this; a 1 N load can alter the axial distortion by 100 μm. While this may not seem like a large value, many machines inherently have this level of variation and as tolerances become ever more stringent, 100 μm becomes a big deal. Dimensional tolerances allowed for the gear geometry will also alter the distortion from press quenching, as slight dimensional changes can alter a material's resistance to bending.

The location of the lower die for Load Case B was chosen by evaluating the low spot from Load Case A (the dark blue area in Figure 6) and placing the die directly below it. The load determined in Load Case A was used and the gap distance adjusted until the beam's straightness

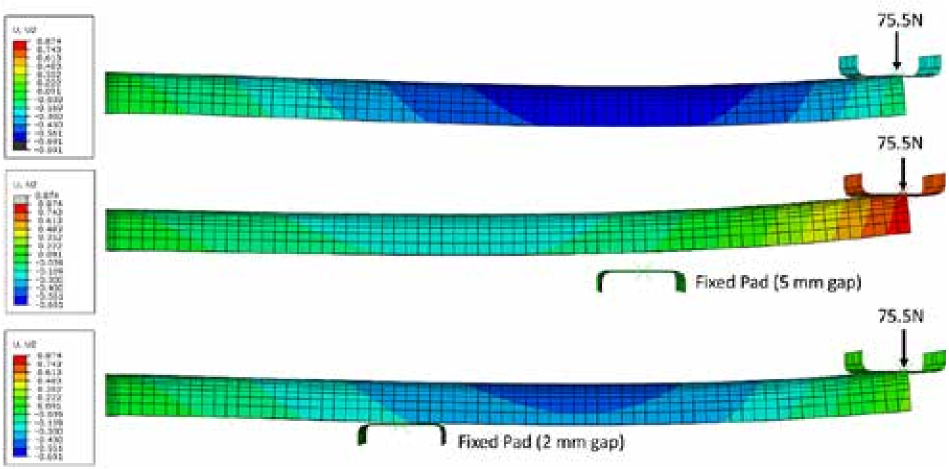


Figure 7: Axial distortion prediction for three load cases with 75.5 N load.

was optimum for the given load. A gap distance of 5 mm, with a 75.5 N load, was determined to be the best for Load Case B. The lower die position for Load Case C was arbitrarily chosen to be approximately 2/3 distance from the free end and the same 75.5 N load was used with varying gap distances. A gap distance of 2 mm, with a load of 75.5 N, was determined to be the best for Load Case C. Figure 7 shows the results for each optimum condition using a 75.5 N load.

Figures 8 and 9 show the tip deflection versus load and total bow versus load, respectively, for Load Case A, Load Case B (5 mm gap distance), and Load Case C (2 mm gap distance). From the two plots, the lower dies for both cases, B and C, help control the deflection and bow very well. Upon first glance, it may seem as though they effectively control the distortion by the same amount. However, the length scale in the plots is millimeters. For larger parts, a few millimeters of distortion may be acceptable, but gear tolerances are generally in 10s, or possibly 100s, of microns. To get a better understanding at these length scales, the plot in Figure 9 has been reduced to loads between 70 and 100 N, with a subsequent rescaling of the total bow, as shown in Figure 10. It can now be seen in Figure 10 that there can be a difference of up to 500 μm between the three loading cases at a given load. Depending on how the processed gear is mated in the powertrain, one bow distortion may be preferable over another. It should also be noted that although the final values for the bow distortion are very similar for a 75.5 N load, the shape of the bow is drastically different, as seen in Figure 7. Heat-treatment simulation can help determine what distortion mode to expect after press-quench processing and aid in the design of better, more effective press quench tooling.

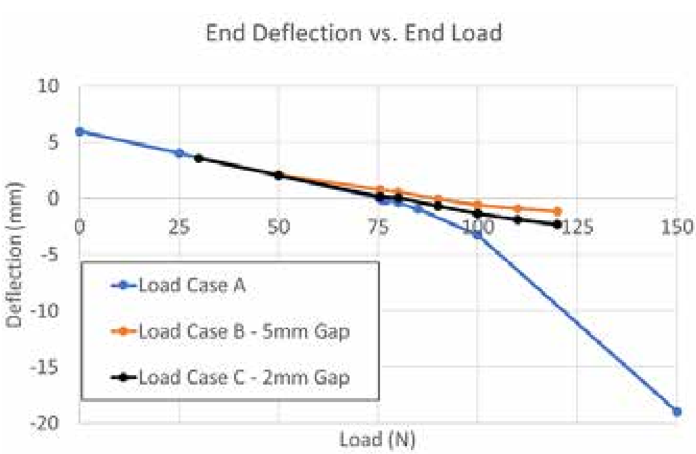


Figure 8: Plot of beam tip deflection versus load for the three loading cases.

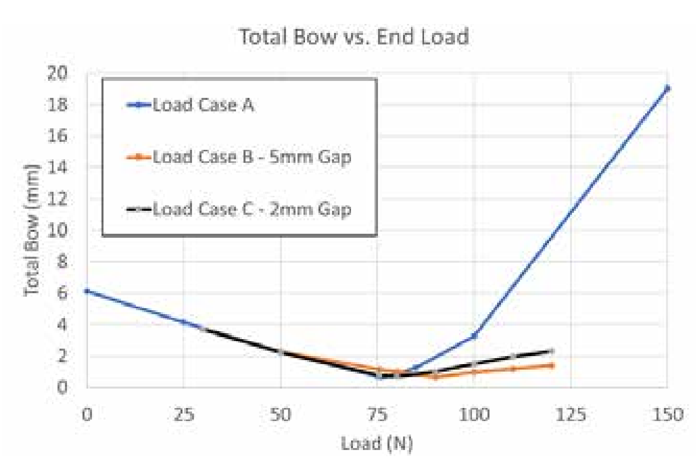


Figure 9: Plot of beam bow versus load for the three loading cases.

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Justin Sims is a mechanical engineer with Dante Solutions, where he is an analyst of steel heat-treat processes and an expert modeler of quench hardening processes using Dante software. Project work includes development and execution of carburization and quench hardening simulations of steel components and analysis of heat-treat racks and fixtures. He has a mechanical engineering degree from Cleveland State University.

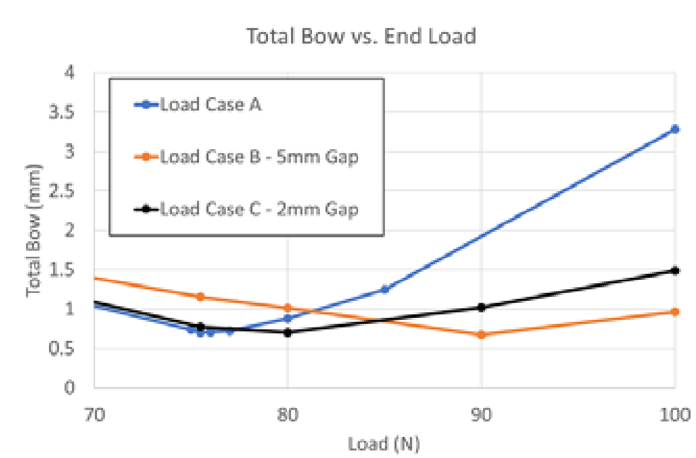

Figure 10: Plot of beam bow versus load for the three loading cases, focusing on the 70 – 100 N range.

D. SCOTT MACKENZIE, PH.D., FASM
SENIOR RESEARCH SCIENTIST–METALLURGY /// QUAKER HOUGHTON INC.

To obtain reproducible results by water quenching, the temperature, agitation, and contamination must be controlled.

Using water as a quenchant

In this short column, we will discuss quenching with water. As a quenching medium, plain water approaches the maximum cooling rate attainable in a liquid. Other advantages include no health hazards, readily disposed, no fire hazard, and readily available. It is also inexpensive compared to other quenchants. Water is used whenever the drastic quench will not cause cracking or excessive distortion. It is widely used for quenching non-ferrous alloys, austenitic stainless steels, and low hardenability carbon steels.

One disadvantage of plain water as a quenchant is that its rapid cooling rate persists throughout the lower temperature range, in which distortion or cracking is likely to occur. Water has a high quenching power (heat transfer coefficient) due to the high specific heat of vaporization and high specific heat capacity. The thermal conductivity is very small compared to most metals. The boiling temperature of water (100°C) is also very low compared to the transformation temperature of martensite for most steels. Because of this, the maximum heat transfer of water occurs at low temperatures. This can contribute to cracking excessive distortion of heat-treated parts.

Consequently, water usually is restricted to the quenching of simple, symmetrical parts made of low hardenability steels. Another disadvantage of using plain water is that its vapor blanket stage may be prolonged, especially at elevated temperatures. This stable vapor phase encourages vapor entrapment.

Local temperature may be increased, resulting in uneven hardness and unfavorable distribution of stress. This may cause distortion, cracking, or soft spots. Water quenched steel parts may rust unless immediately treated with a rust preventive.

TEMPERATURE

The temperature at which water boils (and the maximum cooling rate or maximum heat transfer) occurs within the range of most martensitic transformation temperatures for most grades of steel. Because of the low temperature of maximum heat transfer, and the persistent vapor phase, very large differences in heat transfer can occur. Vapor can persist in holes, cavities, and on surfaces with adjacent parts. Further, the very rapid cooling rate can contribute to large thermal stress, contributing to distortion in quenched parts.

If the water quenchant temperature is increased, two things occur. First, the vapor phase becomes much more pronounced and stable. Secondly, the maximum cooling rate during nucleate boiling decreases. In addition, the temperature of maximum cooling also decreases as the temperature of the water is increased. As the temperature is increased, the cooling rate and resultant thermal stresses decrease, but the transformational stresses increase. This is shown in Figure 1.

In most cases, water quenching is accomplished at room temperature (15-25°C). If the water is not well agitated, then highly variable heat transfer can occur. This is also true of non-symmetrical parts, where large differences in heat transfer can result in distortion or cracking.

At temperatures below 100°C, there is little effect on the cooling curve due to increasing temperature. For steels, there is really no benefit to increasing the water temperature during quenching. For aluminum, for large forgings, there is some benefit to using elevated water quenching. The slow quenching rate reduces the residual stress from quenching. However, the properties suffer. Much better results can be accomplished using a polymer quenchant to achieve desired properties and reduced distortion.

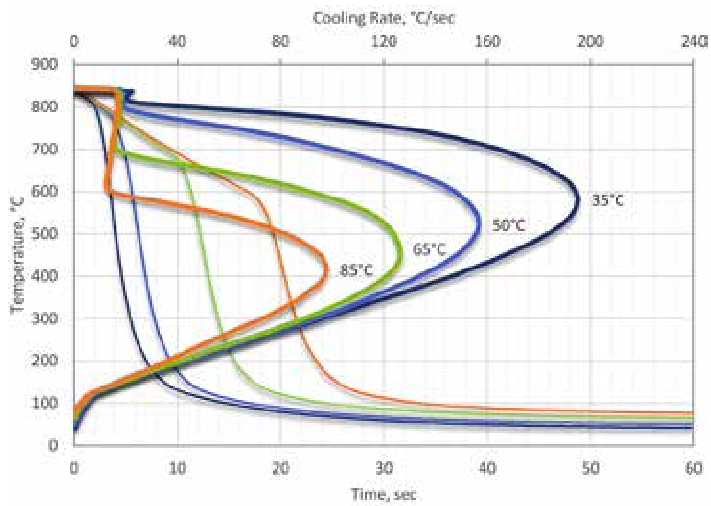

Figure 1: Effect of bath temperature on the cooling curves of water. ASTM D6200 probe.

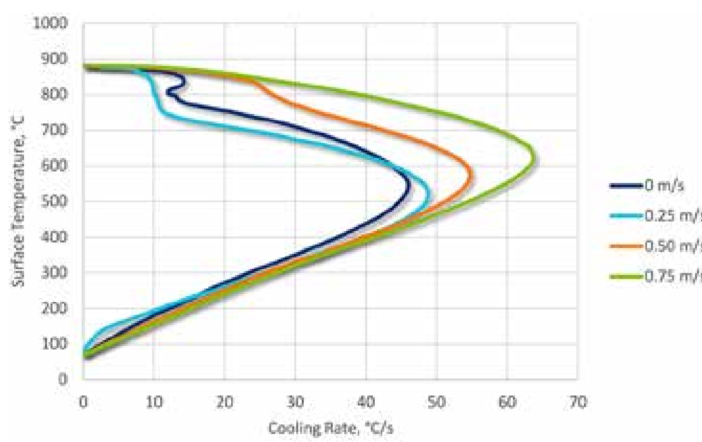

Figure 2: Cooling rate curve for a 25 mm diameter stainless steel probe quenched in 55°C water at different velocities.

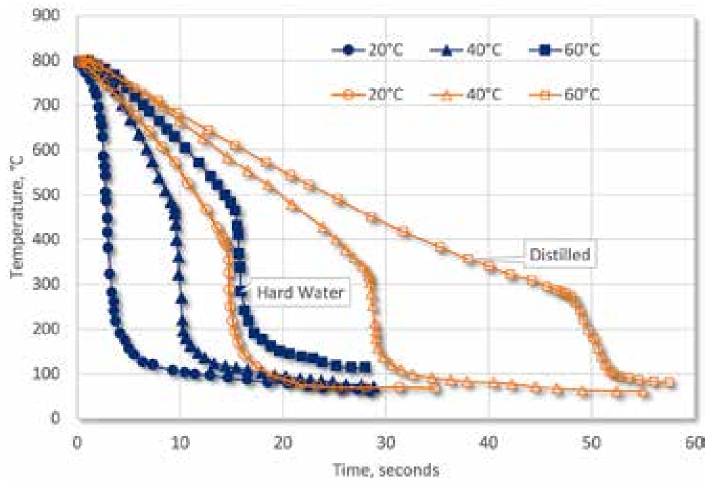

Figure 3: Comparison of the time-temperature curves of hard versus distilled water. The presence of the inorganic constituents of hard water reduces the stability of the vapor phase, and promotes nucleate boiling.

AGITATION

Agitation is particularly important in water quenching because of the very stable vapor phase. The purpose of agitation is to wipe the vapor phase away, and to provide for uniform heat transfer on the surface of the part.

The interaction of temperature and agitation on the vapor phase is much stronger for water than in other quenchants. Therefore, water quenching is generally not used for complex shapes or blind holes. These geometrical obstructions result in a non-uniform heat transfer around the surface of the part due to a persistent vapor phase. In areas of persistent vapor phase, low hardness may result. Cracking can also occur because the local temperature may increase, which will result in shifting the maximum cooling rate to lower temperatures, increasing the transformational stresses (Figure 2).

CONTAMINATION

Contamination is common in the heat-treating shop. With an open tank, it is prone to collecting dust from the shop atmosphere, pollen, and possibly bird droppings. There are also other sorts of contamination such as hydraulic fluids, oils, and scale. Some scale will separate from the part and fall to the bottom of the tank. Other fine scale can be found in the quench water itself, turning the quenchant a dull brown color.

The first group of contaminants are those that are poorly soluble in water. Solids such as soot and liquids that contain soaps, fats, and oils, form suspensions or emulsions that promote vapor phase stability. This results in an increased duration of the vapor phase with a lower temperature of nucleate boiling initiation. Oils, soaps, and fats are the most damaging. As a result, this group increases non-uniform heat transfer. This non-uniformity manifests itself as spotty hardness or increased distortion.

Dissolved gases can also behave in a similar fashion as soaps and emulsions. A saturated solution of air (or other gas) in water will come out of solution during quenching and create a very long vapor phase. This is one reason why is it is recommended to never agitate a quench tank using compressed air.

There are other sorts of inorganic contamination from the incoming water. Depending on how hard the water is, as the water evaporates from quenching or just low humidity, the inorganic content can change the quenching characteristics of the quench. These contaminants decrease the stability of the vapor phase and promote nucleate boiling. If the concentration is high, then the vapor phase may not form at all. This build-up of inorganics can increase the quench rate substantially, to the point where 60°C hard water has nearly the same quench rate as distilled water at 20°C (Figure 3).

CONCLUSIONS

To obtain reproducible results by water quenching, the temperature, agitation, and contamination must be controlled. Water at a temperature of 15 to 25°C (55 to 75°F) will provide uniform quenching speed and reproducible results. As indicated in Figure 1, the surface cooling power of water decreases rapidly as water temperature increases. Hot water has a low heat extraction because, as the boiling point is approached, the vapor phase becomes prolonged. Strong and uniform agitation will reduce the presence of the vapor phase and help promote uniform quenching.

Should you have any questions or comments regarding this column, please contact the editor or myself. Also, if there are any topics that you would like to see covered in this column, please contact the author or the editor.

ABOUT THE AUTHOR

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SHAUN KIM
DIRECTOR OF QUALITY /// BYINGTON STEEL TREATING, INC.

Successful quality control requires clear, consistent documentation. Discrepancies among an order's documents can trip up heat treaters who don't have a plan to handle them.

Settle requirement conflicts before accepting a contract

Resolving conflict among purchase order requirements, drawings, and regulatory requirements can be quite the task when accepting contracts for heat treatment. Unfortunately, it happens more often than we would like. If your company is in the AMS/ NADCAP sector as my company is, the ramifications for overlooking these conflicts can be very damaging not only for any upcoming audit, but for the confidence of your customers in your ability to produce conforming heat-treatment processes.

Although I am speaking from the lens of a NADCAP processor, these problems are applicable to commercial work as well. Often the customer is unaware of these conflicts — they do what is required by following their flow-down requirements to provide all the documentation needed to the heat treater. I can't speak for everyone, but I think most quality departments are always happy to get as much documentation as we can. However, extra documentation can open the door to conflicting requirements. These conflicts can lead to extra communication with your customer, which in turn can force your customer into extra communication with their customer (depending on how far down the supply chain goes), and the trickle down keeps going until the OEM/end user is involved to resolve a conflicting requirement. It doesn't always happen like this, but it can, and I have gone down this route many times. Undoubtedly, this puts some pressure on heat treaters to navigate the documents during contract review and locate language that directs them to certain requirements, specifications, or exclusions.

This article will focus on the dangers of overlooking contract review and how to mitigate conflicts between documents.

We've all seen this before at one point in our careers regardless whether it's commercial or AMS/NADCAP work. It's probably something you see weekly or even daily. A PO comes in with requirements clearly defined, and a drawing attached has conflicting language or requirements. Or, in another situation, a PO comes in with a referenced specification to process to, and there is a conflict between PO and specification requirements. What happens when this situation occurs? Some quality representatives will say the PO is the superseding document, and others will say the drawing is the superseding document. The same can be said for PO requirements that conflict with specification requirements. This may sound a bit strange to some readers, but in my opinion, there is no right or wrong way to mitigate this issue. It all depends on how your own quality system works — what your procedures direct you to do in these situations, and how much risk you are willing to put on your company.

I prefer to stick to the conservative route when addressing these issues. What does "conservative" mean? In my case, I want to document all the issues and put them in writing either on the PO or through written correspondence rather than verbally accepting changes or overlooking issues that are significant or even insignificant to the process. If there is any conflict between documents, I prefer to make sure that our customers are aware of why changes need to be made and to make certain that we are following the requirements that allow us to give quality heat treatment.

If you fail to mitigate conflicts between documents, you have the potential to process non-conforming product for your customer, delay customer lead time, diminish confidence in your company, and erode their relationship with their customers.

How do you accomplish this? The answer is simple because it is usually the easiest and most efficient way of closing all the gaps that concern you: Document everything. If there is a conflict between the drawing and PO, have it identified on the PO with the customer accepting a deviation or acceptance of a conflicting requirement. The same can be said when a specification is referenced: Document it. Get the deviations or acceptance documented on the PO.

An example among many that can occur could be a PO calling for 17-4 CRES material and heat treat in accordance with (IAW) AMS 2759/3J to H-1050 condition, which is in the range of 32-38 HRC. Then you review the drawing and see that the "H" condition is not specified, but instead you see 31-38 HRC is requested IAW AMS 2759/3J. There is a conflict between the PO and the drawing because, although you can technically meet the HRC requirement by heat treating to H-1050 (as long as your lowest hardness reading is above 31 HRC), the range that is specified on the drawing is calling for H-1075 condition based on the hardness range documented in AMS 2759/3J. Being mindful of this conflict, and using my conservative approach, I would want a revised PO to call out the correct condition before accepting this. Big conflict or small, I don't have a filter in this sense. It's either correct or it's not. Some would argue it's stubborn, not industry practice, or not conducive to reaching OTD goals because extra communication will slow the process. I don't care.

For my company, process conformance, NADCAP accreditation, company accreditations, and audit performance take precedence over any OTD goal set. Again, everyone has their company's interests at heart when making these choices. It's up to you to decide what is more important. For me, I would prefer to have conforming product and not get an audit finding on something that was an easy fix with a little communication.

I can almost hear readers asking, "What happens if my customer understands the conflict but is unwilling to change their PO?" As I have alluded to earlier in the article, every company has their own quality system and chooses what is best for them. That said, there may be more than one option at your disposal. Speaking for my company, we would reject the job and send it back. Based on experience, often a customer will change their tune once you tell them you won't process for them unless the conflicts are addressed. Your customer can't force you to do anything your company is not comfortable doing. I have done this before, will have to do it again, and know that my CEO understands and supports my stance on this.

The choice is ultimately yours, but make sure you are supported in your decision making.

What could go wrong if you don't address these conflicts? There are several things that could go wrong and too many to name. But, in my opinion, there are two things that matter the most. The first thing is your customer. If you fail to mitigate conflicts between documents, you have the potential to process non-conforming product for your customer, delay customer lead time, diminish confidence in your company, and erode their relationship with their customers. The second thing is your own audit and the potential to leave yourself vulnerable to audit findings. Objective evidence is the name of the game when going through an audit, and when you fail to provide this in the form of documentation, you have failed in providing the evidence that you have identified and addressed these conflicting requirements. I know for certain no one wants these things to happen.

There is no right or wrong answer to address the issue of conflicting documents. This is not a one-size-fits-all solution, and there are instances where it would need to be handled on a case-by-case basis. For me, one thing is empirical — documenting any conflicts can be applied and benefit any quality system. I have seen a great deal during my time as quality director, but two things I've never encountered were a customer complaining about Byington Steel's thoroughness when performing contract review, or an auditor telling us we have too much documentation supporting our processes.

We plan to keep it that way.

ABOUT THE AUTHOR

Shaun Kim is the Director of Quality at Byington Steel Treating, Inc. Contact him at skim@byingtonsteel.com.

HEAT TREATMENT OF GEARS

The benefits of close interaction between gear designers and heat-treat specialists can lead to total cost and quality optimization.

By BILL DISLER

Often the options of heat treat may feel pre-defined when looked at from a gear designer's perspective. There are options, but both gear designers and some heat-treat manufacturers are constrained by limited exposure to the fundamental physics that drive the process performed by the equipment available. The heat treat industry is old and rich with experience, but it moves slowly without the proper incentives to change. It is important to recognize the benefits of early, constructive dialog between gear and powertrain designers and heat-treatment experts to advance system features and designs to the overall benefit of cost-effective performance of quality powertrain systems.

The objective of this article is to touch on some of the key elements of heat treatment at the fundamental levels to impress upon readers the benefits and limits of commonly discussed methods. In some cases, older methods with newer packaging can be a foundation for progress. The science of our processes has not changed much over the last several decades. The focus of this article is carburized gears, but most of the fundamentals discussed can be applied in other heat-treat processes when the benefit can bring value.

A REAL-WORLD EXAMPLE – LARGE DEEP CASE GEAR OPPORTUNITIES MISSED

In this case we're talking about wind-turbine gears — gears that can weigh in excess of 1,500 pounds (680 kilograms). The pressure created by surface winds apply extreme force to the turbine nacelle and the structure supporting the gears and rotating gear mass. Gears, no matter the application but especially in wind turbines, are expected to operate with as little noise as possible. To effectively operate in such harsh conditions, most wind-energy gears are carburized and quenched. Pit furnace systems are the most commonly used equipment. The driving force in selecting this technology is the very long carburizing time related to quench utilization. Multiple pit carburizing furnaces can be serviced by one shared quench tank. When carburizing times are measured in days, utilizing multiple carburizing chambers with one quench tank is logical. However, when the overall gear design is taken into consideration to include both heat-treat and hard-grinding processes, opportunities exist to significantly improve manufacturing cost and overall quality.

The fundamentals of this carburizing and quench process are sound, but the physics of the mechanisms are not being considered. Keep in mind that thousands of these systems are being used for large gear processing around the world today. Carburizing en masse for deep-case parts makes sense. Beyond the awkward material handling and the undesirable product-to-fixture load ratios, the quench configuration is the true weakness. These systems use oil to quench the parts, which is a time-tested and proven process. Here is where physics comes in and the problems grow.

The oil quench system used is a vertically elongated quench chamber. It is simply not possible with such massive loads to get uniform high volume oil flow from the bottom to the top of such loads. Since oil boils when it gets too hot, there is an inevitable non-uniform cooling of these gears that leads to dramatic distortion. The more uniform the heat transfer during quench, the lower and more predictable the distortion you will see. Gears can be designed to compensate for predictable distortion.

Oil by nature is a multi-phase quenchant when used in heat-treat quench applications. This means there will always be more than one type of heat transfer occurring in a load, no matter what we do in quench designs: the heat transfer of liquid oil (convection), film boiling heat transfer, and the heat transfer into oil vapor (bubbles) when it all out boils. The differences of these heat transfer rates are dramatic (Figure 1).

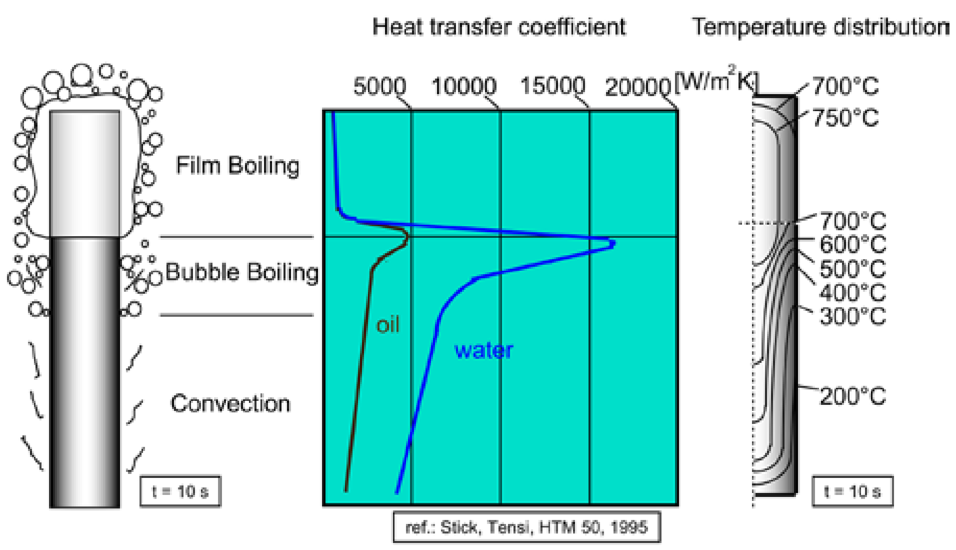

Figure 1: Changes in heat transfer rates for multi-phase quenchants – oil and water.

For those of a less technical mindset, consider thawing something frozen for dinner. Let it thaw in air (vapor) or put it in water (liquid). The same physics principles are involved. All oil quench tanks have agitation — or they should — to minimize the formation of vapors that create non-uniform cooling of the parts. In an optimum situation, you want enough flow to absorb heat into the oil and take the oil away (convection) before it gets to a temperature of phase change. There are also detrimental effects from too much agitation, so we really want a sweet spot of 2-3 feet/second in an optimum world. (See Figure 2)

The quench tank in a pit furnace setup is the worst-case scenario, as the agitation is from the bottom to the top of the elongated tank.

There is no way, regardless of how aggressive the agitation may be in the bottom of that tank, to have any uniform, much less laminar, flow through the load. Even with high flow at the bottom, the top of the tank will act closer to still oil. In addition, the mass of the gears creates voids of flow between themselves due to the needed vertical fixture. (See Figure 3)

The way the parts are configured within a load is very important to the uniformity of any quenchant's flow. By using CFD flow modeling, fixturing can be optimized to improve flow. As an equipment supplier, I can say with experience this technology is seldom used early in a project, but often used to solve problems later in production. Figure 4 shows how CFD modeling can help with progressive quench system designs. Imagine what a flow model would look like if applied to a pit furnace quench tank.

During tests done in a conventional sealed quench batch furnace with a much more optimized oil quench configuration, it was found that a decrease in distortion could have a substantial impact in reducing the amount of costly hard grinding needed for these gears. It could also allow a decrease of carburizing time by almost one day — more than 20 hours of furnace time. The reason is the gear could be designed with less planned waste material, as the reduced distortion would minimize that requirement due to the improved quench method applied. Of course, using conventional sealed quench batch furnaces, each with their own quench tank, is not a cost-effective or practical solution for a number of reasons. However, the lessons learned can lead to new designs of equipment applying conventional technology in a new package. These alternatives exist and bring with them improved automation, improved quality of the parts, and much lower overall part costs.

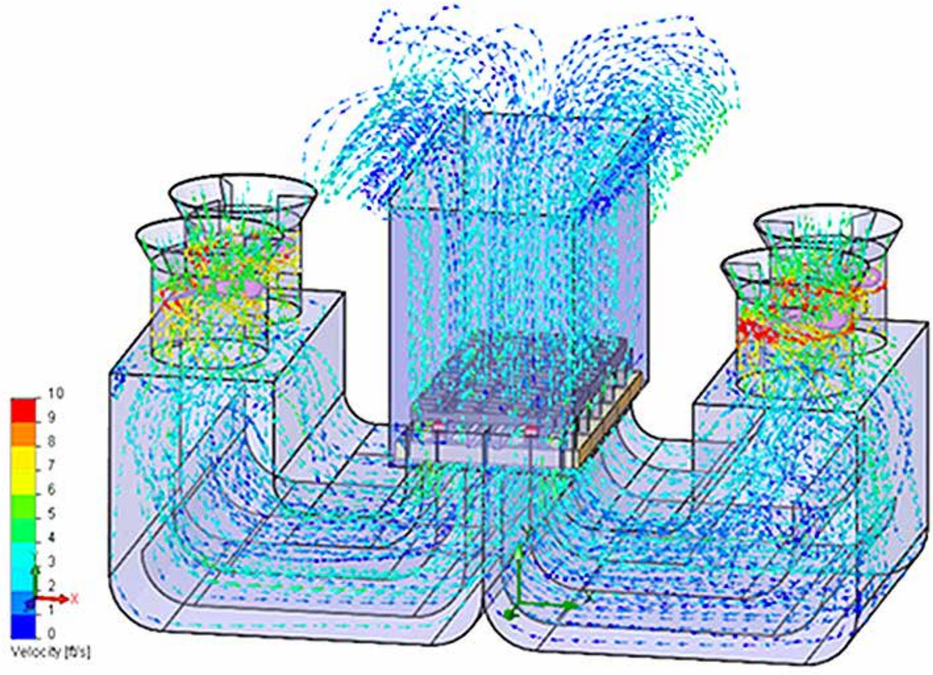

Figure 2: Laminar quench flow in optimized quench tank design.

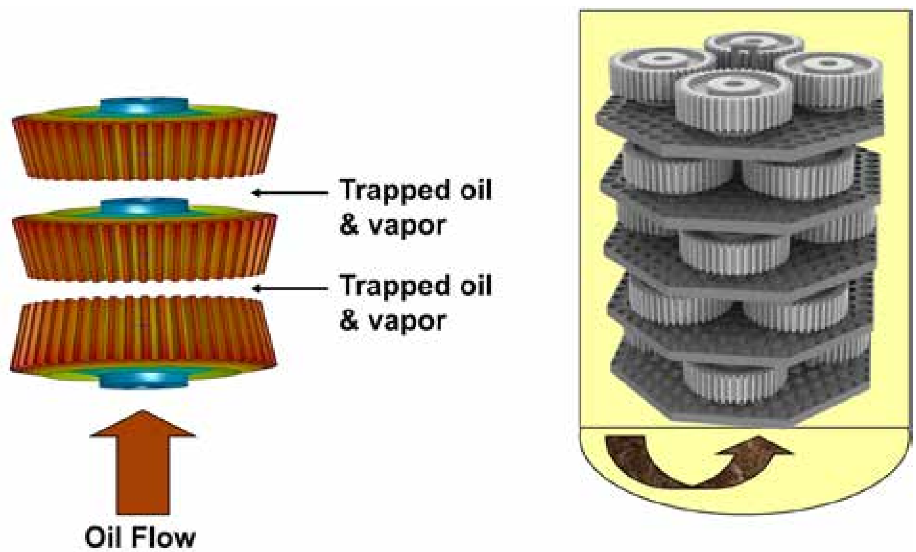

Figure 3: Typical configuration of fixtured parts in pit quench system.

But today, pit furnaces remain the primary solution purchased for heat treating such large, extremely deep case gears as are used for wind energy. Why? To take advantage of this change in heat treatment approach, the actual gear design, upstream of heat treatment, must be changed. In many companies, there is not an optimal channel of communications, and the actual Value Add that could be seen is not easily conveyed.

THE HEAT-TREAT BUILDING BLOCKS GEAR DESIGNERS (AND FURNACE ENGINEERS) SHOULD UNDERSTAND

1. Heating and holding parts at temperature during carburizing and other processes.

a. Temperature specification for a process chamber may be common, but what the actual part experiences in one system vs. another is not the same — and it can matter.

b. When comparing a continuous furnace to a batch furnace, regardless of process (atmosphere carburizing, LPC, nitriding, tempering, etc.), parts will experience more uniformity in continuous furnaces.

c. In addition, in a comparison of a processes, parts experience better uniformity with a continuous process vs. a batch process. The reason is that although the chambers may be validated to common uniformity specifications, a part/load moves through a continuous furnace, and, hence, the parts experience an averaging effect of the highs and lows within the acceptable specification band. In a batch chamber, the parts are stationary and one part vs. another in the same load will experience the full variance of the tolerance allowed.

Consider a ±10°F temperature specification in the typical carburizing furnace. That is a 20°F total spread. Although the significance to the quality results of what the parts see will vary based on case depth and process, consider that a change of 100°F in carburizing temperature either doubles or halves the case depth. If you are striving for higher and higher quality, this might matter.

2. Atmosphere options for carburizing — conventional endothermic

gas vs. LPC-based approach — understand the pros and cons of both

a. Endothermic carburizing gas, either created by a generator or through a blend of nitrogen and methanol directly in the furnace, is controlled via sensors inside the furnace throughout the cycle, allowing compensation for load size variations.

i. These processes displace air in the chambers with the gas, but will have trace levels of oxygen remaining.

ii. Cycles are fairly "text book" with respect to carbon potential and case-depth creation.

b. LPC uses alternating acetylene and nitrogen throughout the cycle to carburize, with no sensors inside the furnace involved throughout the process.

i. LPC chambers use vacuum to remove air from the chambers and backfill with carbon-rich gas; hence, virtually no oxygen remains in the chamber.

ii. Cycles can be simulated, but testing is required to dial in the exact process for each specific load of parts — the results depend on exact load surface area each time, so partial loading is not possible.

iii. With no trace air, inner granular oxidation (IGO) can be eliminated, and this can be a benefit in some cases.

1. LPC processes come with a price, so be certain the IGO benefit applies to the application; often, it does not due to the failure points of the gear or the post-process grinding requirements.

iv. Acetylene carries about six times more carbon than conventional endo atmosphere and can offer faster cycle times for light-case parts.

1. After a short carburizing time, the benefit of this surface carbon activity is overridden by carbon diffusion physics within the part. In mid- to deep-case carburizing, it is unlikely that the process times will differ in a significant way.

2. The same can be expected for case uniformity when measured from the root to the face of a gear — with a shallower case, the benefits are likely to be more pronounced; with a deeper case, it will be less so.

v. Viable temperature increases to shorten carburizing times, and their adverse effect on microstructure apply to both LPC and conventional atmosphere systems.

c. Complications are created when using vacuum in continuous furnaces, so LPC is typically constrained to batch only processes.

3. Quench media and load size — key considerations to minimize distortion (a newer way to look at this topic)

a. Quench media, in my opinion, should be grouped into two main categories:

i. Multi-phase quench media: oil, water, polymer.

1. Each of these will experience phase changes during quench, which leads to non-uniform heat transfer in the parts, regardless of what is done in machine design.

2. Although oil is a multi-phase quenchant, when used properly, it remains a high-quality, flexible solution that meets the needs of many gears and other components.

ii. Single Phase Quench Media: Compressed Gas or Molten Salt

1. These will not experience a phase change during quench and, therefore, will provide the most uniform heat transfer from the part during quench.

2. Compressed gas, typically nitrogen or helium (which has a better heat transfer coefficient but is no longer viable), has very limited heat-transfer properties.

3. Salt has better heat-transfer properties and is often blended with small amounts of water if even higher heat transfer rates are required.

iii. In all cases, circulation is a major consideration.

b. The smaller the load, the better quench uniformity can be in all cases.

i. This again is the intersection of physics regarding how one can get flow uniformly through the load.

c. Figure 5 shows approximate heat transfer rates for common quench media options.

Some words about using salt as a quench media: It has a stigma from the past of being a nasty media with all kinds of safety and

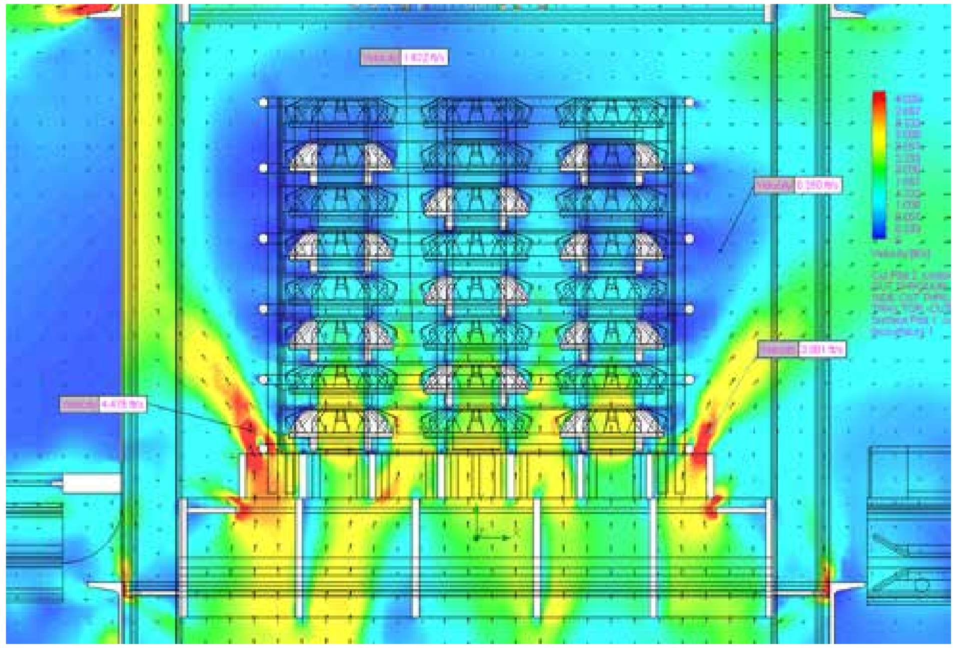

Figure 4: Quench flow CFD model through fixtured parts.

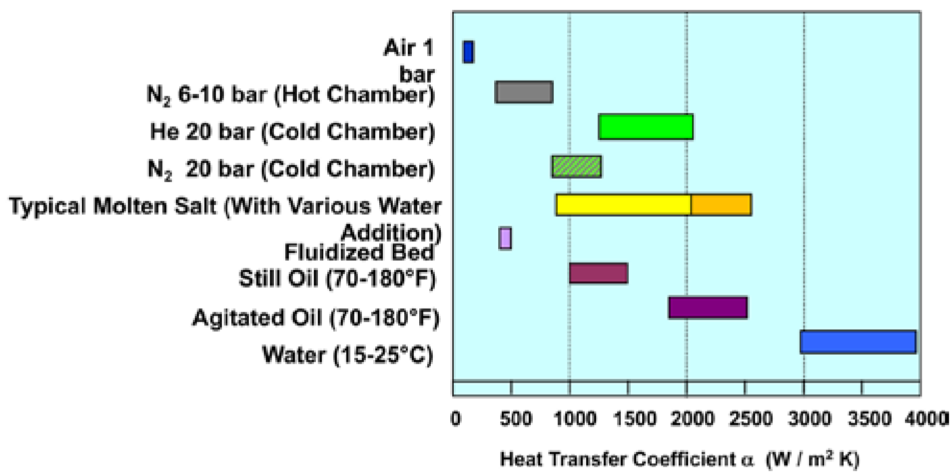

Figure 5: Heat transfer rates of common quench media.

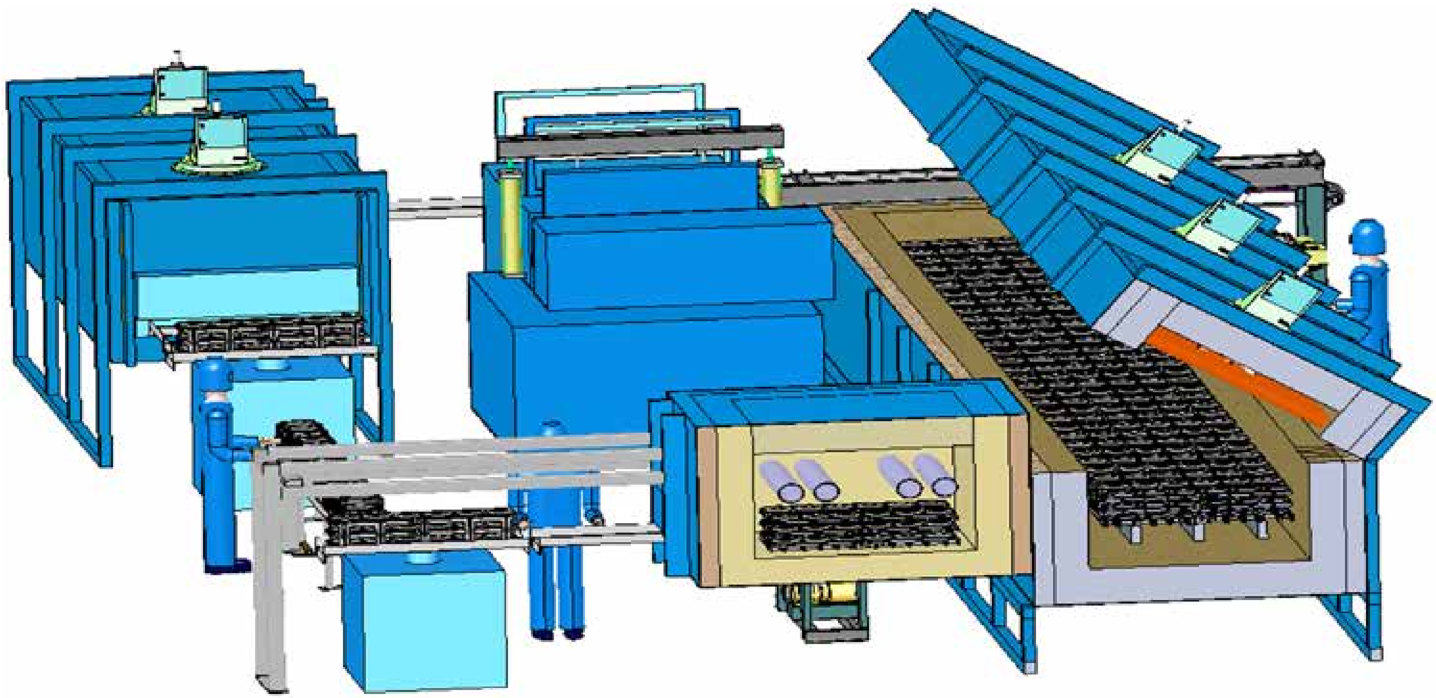

Figure 6: Future modular system with salt quench.

environmental issues. Often, when I mention salt quenching, I get looks from seasoned heat-treat experts like I am crazy. It is very important that people understand salts better to open opportunities for the future. The salts being referred to in this article are 99-plus percent recycled, and what is left can be easily discarded, unlike oil. Salt used in these quench systems is very green and environmentally friendly. Further, with new sensors being developed, the heat-transfer rate of salt with small amounts of water added can be controlled and become an added factor to tailor many processes. Demand for salt quench systems is growing. In some cases, this is because it can do things no other media can, like quench to bainite with a 700°F quench temperature. In other cases, it is being considered for martensitic quench processing to provide better heat-transfer rates for those who have seen the benefits of gas quench systems but do not want to deal with the poor heat-transfer rate limitations. Like everything, it has limitations and aspects to be considered for its application, but due to its mechanical properties, it may be worth considering.

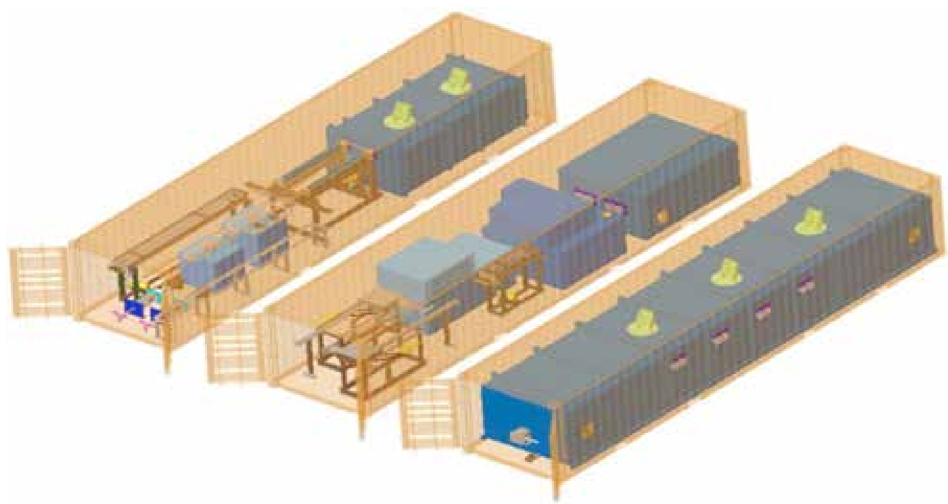

Figure 7: Redeployable heat-treat systems.

I encourage gear designers to reach out and explore the evolution of heat-treatment processes. Heat-treat systems tend to evolve slowly compared to other technologies such as metal cutting and automation, but they do evolve and can do so in the most efficient way when gear designers engage and explore options together with their suppliers. Much of what can be done is limited by physics, but creative packaging will allow for much more flexible and accommodating systems in the future. Although not explored in this article, changes are coming with other aspects of heat-treatment systems. As an example, consider the modular system shown in Figures 6 and 7.

This system is designed for fast installation on flat floors, is easily re-deployable similar to CNC machines, can process moderate sized loads to balance flexibility and cost per part, has small load quench benefits, and uses salt quench for environmentally friendly, low distortion quenching. Change can happen when gear designers and heat-treat equipment experts work together to develop a vision of their future needs.

ABOUT THE AUTHOR

Bill Disler is president and CEO of AFC-Holcroft L.L.C. He also held a previous concurrent title of chairman of the Board of ALD-Holcroft, a joint venture between ALD GmbH and AFC-Holcroft. Other previous positions include leading the opening of an induction heat treatment business unit for a major Japanese company through its Gear Technology Center, design and implementation of automation and cleaning systems at a large global automation, an industrial cleaning company serving the metal cutting equipment in gear centers and other powertrain related systems, and working hands-on in the field as well as in engineering at Holcroft early in his career after earning his degree in electrical engineering.


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AN INTERPRETABLE MACHINE LEARNING BASED APPROACH FOR PROCESS TO AREAL SURFACE METROLOGY INFORMATICS

This article presents a new framework based on the ridge Mamdani fuzzy logic system for the mapping of process features to areal surface metrology parameters.

By OLUSAYO OBAJEMU, MAHDI MAHFOUF, MOSCHOS PAPANANIAS, THOMAS E MCLEAY, and VISAKAN KADIRKAMANATHAN

Surface metrology parameters represent an important class of design variables, which can be controlled because they represent the DNA or fingerprint of the whole manufacturing chain as well as form important predictors of the manufactured component's function(s). Existing approaches of analyzing these parameters are applicable to only a small subset of the parameters and, as such, tend to provide a narrow characterization of the manufacturing environment. This article presents a new machine learning approach for modeling the surface metrology parameters of the manufactured components. Such a modeling approach can allow one to understand better and, as a result, control the manufacturing process so that the desired surface property can be achieved while manipulating the process conditions. The newly proposed approach uses a fuzzy-logic-based-learning algorithm to map the extracted process features to the areal surface metrology parameters. It is fully transparent since it employs IF… THEN statements to describe the relationships between the input space (in- process monitoring variables) and the output space (areal surface metrology parameters).

Furthermore, the algorithm includes a ridge penalty-based mechanism that allows the learning to be accurate while avoiding over-fitting. This new machine-learning framework was tested on a real-life industrial case study where it is required to predict the areal parameters of a manufacturing (machining) process from in-process data. Specifically, the case study involves a full factorial experimental design to manufacture 17 steel bearing housing parts fabricated from heat-treated EN24 steel bars. Validation results showed the ability of this new framework not only to predict accurately but also to generalize across different types of areal surface metrology parameters.

1 INTRODUCTION

Surface metrology, defined as the science of measurement of small-scale characteristics (such as amplitude, spacing and shape of features) in manufactured parts [1], forms an important part of the manufacturing processes for two main reasons. The first relates to the fact that surface metrology can be thought of as the fingerprint of the whole manufacturing chain. This fact can be used for control of the manufacturing process [2, 3]. The second reason is that surface metrology can directly correlate with the manufactured components function. Such information is useful for quality assessment and function prediction.

Predicting the quality or how a manufactured component will function is particularly valuable in helping to meet today's ever tighter budgetary and time constraints as well as the drive for right-first-time production of materials [4]. Indeed, a mechanism for controlling the surface metrology parameters can represent a valuable asset as evidenced by the plethora of research studies that have sought to design algorithms for this purpose [1, 5, 6]. However, before such a control can take place, a mapping from the process conditions to the surface metrology variables must be found. Such a mapping has formed the topic of many research studies for several decades as will be discussed in the next section. The majority of these research studies focus on very simple mappings typically involving the creation of a limited list of input features from the process data. A data model is then found to map these features to selected surface metrology parameters (usually profile parameters).

One notable example is the prediction of the surface roughness heights (Ra) from process conditions [5-7]. It should be noted, however, that these existing studies have mainly focused on predicting the profile parameters, and the application of modeling algorithms for predicting areal parameters, which are arguably more important, is limited [8]. The areal parameters provide a characterization for the full 3D surface of the manufactured part and have been shown to be more descriptive of the surface as well as being better related to its function [8]. Therefore, mappings from process conditions to areal parameters can provide better value for the manufacturing process. This research study will therefore mainly focus on the modeling of the areal surface metrology parameters.

Existing research studies also typically focus on very small subsets of areal parameters while neglecting the others. They also tend to derive coarse scale features extracted from the process data [9, 10]. However, as discussed in [5], many areal surface metrology variables can correspond to a particular function, and, as such, it is often imperative these areal parameters be combined in a systematic way for function prediction. The surface metrology variables can vary in a very different and sometimes unpredictable manner; an approach formulated for predicting one areal parameter might not be applicable for predicting another areal parameter.

As the algorithms hitherto developed have only been validated on one or two areal parameters, it is difficult to make a concrete statement on how such modeling approaches perform across the many areal parameters. Consequently, validating the published algorithms on the other areal parameters (which may perhaps be of equal or more importance depending on the use of the variable) may prove to be problematic.

The study in this article proposes a new framework to predict areal surface metrology parameters based on features extracted from process conditions. The proposed approach is shown not only to generalize across unseen data, but is also robust enough to be utilized for all the 24 areal surface metrology parameters on which the proposed approach is tested.

To validate the developed algorithms, a full factorial experimental design was carried out to manufacture 17 steel bearing housing parts as a case study. The sparse and highly uncertain multidimensional data obtained during this case study represent real manufacturing processes where components are manufactured in low volume. Therefore, the main contribution of this article is the development of a modeling methodology that can generalize to a large number of manufacturing variables using a limited quantity of data.

The details of the experimental design as well as process conditions are discussed in Section 3. The proposed framework presents methodology that can aid the drive toward manufacturing automation and data exchange [11]. The review paper by [12] describes state-of-the-art in terms of algorithms, industry uptake, and investments across a wide-range of manufacturing industries. For different materials and manufacturing processes, machine learning approaches, such as artificial neural networks, have also been developed with limited experimental data for predictive modeling of properties of manufactured components [13].

The properties of the components can be dictated by the properties of the material, mechanical or microstructural, but also via surface metrology parameters within a synergetic framework. There is a plethora of applied research works relating to the causality between process and material data and mechanical and microstructural properties, but there is little work on such causality with respect to surface metrology parameters. This holistic approach should improve our understanding of how the final properties of manufactured components may be optimized for right-first-time production.

Symbol	Name	Formula	Notes
Sa	Arithmetic Mean Height	$\frac{1}{A}\iint_A \lvert z(x, y)\rvert dxdy$	This is defined as the arithmetic mean of the absolute of the ordinate values within a definition area (A). This parameter can correlate with friction of manufactured components
Sq	Root Mean Square Height	$\sqrt{\frac{1}{A}\iint_A z^2(x, y)dxdy}$	This is the root mean square value of the ordinate values within a definition area (A). Sq can relate the way light scattering effects from a surface.
Ssk	Skewness	$\frac{1}{Sq^3}\frac{1}{A}\iint_A z^3(x, y)dxdy$	This is useful for the measurement of surface symmetry about the mean line.
Sku	Kurtosis	$\frac{1}{Sq^4}\frac{1}{A}\iint_A z^4(x, y)dxdy$	This is the quotient of the mean cube value of the ordinate values and the cube of Sq within a definition area (A). It measures the profile symmetry about the mean line.
Sdq	Root Mean Square Gradient	$\sqrt{\frac{1}{A}\iint_A\left(\frac{\partial z^2}{\partial x}+\frac{\partial z^2}{\partial y}\right)dxdy}$	This parameter is particularly useful in sealing applications.
Sdr	Developed Interfacial Area Ratio	$\frac{\sum\sum A_{ij}-A}{A}$	The Sdr parameter has a direct correlation with surface adhesion. ISO 25 178 part 2 defines the Sdr with integrals instead of summations.

Table 1: Selected areal parameters as defined in the ISO documents. The derivations of some of these parameters are shown in Figure 3. It should be noted that the data is sampled uniformly along the x and y axes. Z(x, y) represents the measured height at location (x, y).

The remainder of the article is organized as follows: Section 2 presents a detailed literature review of existing techniques, which have been used for mapping process conditions to surface metrology variables. The section details the strengths and weaknesses of these approaches to the overall manufacturing informatics system. As already mentioned, Section 3 provides a detailed description of the experimental procedure for which the data has been derived. Section 4 discusses the proposed interpretable fuzzy-based machine learning approach for the surface metrology informatics system. Section 5 presents and discusses the results while Section 6 provides the conclusion, which can be drawn from the studies conducted from the paper as well as providing suggestions for future research.

2 EXISTING LITERATURE

The book by Whitehouse [1] may perhaps be described as the most important piece of literature where the use of surface metrology in manufacturing for function prediction and quality control is perfectly detailed. The book forms the foundation of many research studies, which have investigated the use of surface metrology components to predict manufactured components function and consequently to control the manufacturing process. Controlling the manufacturing process is typically achieved by the manipulation of the process parameters. To achieve such a control framework, it is apparent that a model indicative of how the process parameters affect the surface metrology parameters must be identified [14]. Such a mapping framework has been the subject of many research studies as already discussed in [5, 6].

Surface profile parameters account for the majority of surface metrology variables used for understanding the manufacturing chain. Of the profile parameters defined in the ISO standards [15], the surface height (Ra) is the most widely used because its derivation is simple, fast, and its meaning is widely understood by manufacturing technologists. For example, a high value of Ra indicates a visually rougher surface. Predicting the Ra accounts for the majority of the surface profile predicted variable studies. Some of these studies include the prediction of surface roughness parameter (Ra) for a computer numerical con- trolled (CNC) milled surface using linear regression [16] and the assessment of surface roughness using time and frequency domain features for a polished surface [17]. In particular, the studies conducted in [18] have shown that the Ra strongly correlates with the mean and root-mean-square (RMS) of the vibration signals for the polishing process.

However, one of the main limitations of the approach is that predicting the Ra may not be sufficient to fully characterize the manufacturing informatics system. This is because the Ra value is very simplistic and may not account for the variation across the surfaces [17]. One solution to this, which has been proposed in the literature, involves creating a distribution of Ra values, but this has not been widely adopted by both academia and industry perhaps due to the complexity involved [19]. A better and recent approach relates to characterizing the full surface as opposed to using profile parameters. This recent approach is known as the areal surface, and it is the main subject of this article.

One of the most prominent studies in attempting to predict the areal surface parameters relates to the prediction of the Sa parameter

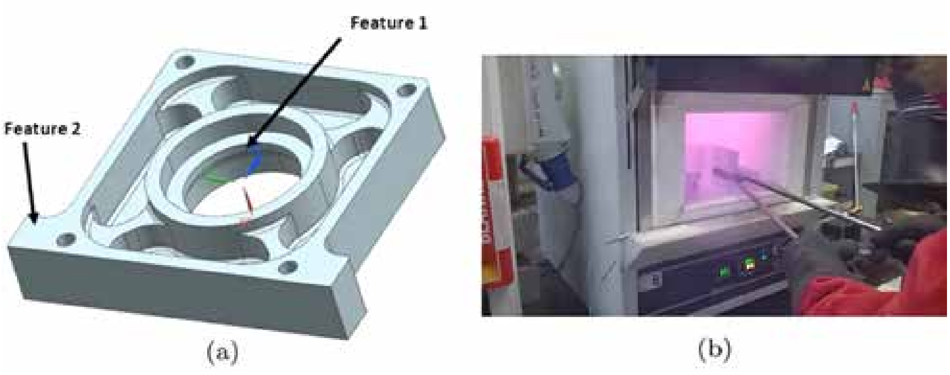

Figure 1: (a)CADmodel of the manufactured part. Two features were measured for the purpose of surface metrology analysis. Each feature labeled is associated with one or two operations, which correspond to the machining process component, which produced the feature. (b) Heat treatment of the steel blocks.

Figure 2: Machining process.

Run Order	Parts	Material Hardness	Feed	Spindle Speed	Datum Error
1	13	Hard	Rec	+ 20%	0 mm
10	24	Soft	Rec	Rec	0 mm
11	21	Soft	+ 20%	Rec	0.02 mm
15	6	Soft	+ 20%	Rec	0 mm
17	23	Hard	+ 20%	Rec	0 mm

Table 2: Full factorial experimental design variables for five of the 17 manufactured parts. Note that "Rec" stands for recommended setting.

for a rotating machined process from process variables as included in [19]. The areal parameters characterize the full 3D surface and have been standardized in the ISO25 178 documents [20]. These documents contain a comprehensive industry standard areal parameters. The parameters as well as their use are shown in Table 1. Many of the algorithms formulated for the prediction of areal surface parameters have only been applied to one or two of the areal parameters [8]. Validation of such approaches on the parameters on which they have not been tested may not be feasible. This article presents a fuzzy modeling approach for the prediction of surface area metrology parameters.

The proposed approach is tested on 24 areal parameters in order to show the proposed approach can be generalized across the various surface metrology parameters. The paper in [21] provides an excellent overview of the use of fuzzy models in areal surface metrology predictions. Fuzzy logic systems provide a unique modeling approach of leading to interpretable but non-linear input/output mapping when predicting the surface metrology parameters. Manufacturing systems are in the middle of a revolution where different components and stages of the manufacturing process are increasingly becoming "intelligent." This intelligence stems from the fact the many components involved in this process are increasingly able to intercommunicate from upstream to downstream. This special ability is embedded in the concept of Industry 4.0, which references the fourth industrial revolution in which machine components and processes are equipped with cyber-physical capabilities and are thus capable of tuning their process conditions in response to feed- back from the environment and other manufacturing conditions. The promise of Industry 4.0 is well discussed in [22]. Surface metrology represents a key enabling component of this revolution as surface metrology parameters play a key part in the inspection of manufactured components. The surface metrology parameters can provide insights for online decision making in a cyber-physically connected system. The Ra, for example, is a design variable, and it is typically required to not exceed a particular limit for the manufactured component to function as expected.

3 EXPERIMENTAL DESIGN

A full-factorial experimental design (see Table 2) was performed on a steel bearing house [22]. The CAD model of the product to be manufactured is shown in Figure 1a. Using a Vecstar furnace, the material blocks (steel EN24) were heat treated to approximately 845°C (Figure 1b) and then quenched in oil so they can be hardened. The next step involved tempering at the selected design temperatures. Temperature gradients and variations during both heating and tempering were also measured using high-temperature thermocouples. The surface hardness measurements of the blocks were obtained using a Rockwell device. The treated product was then machined (Figure 2) using a DMG MORI NVX 5080 3-axis machine with variable controlling factors to arrive at the final manufactured component. During the machining process, process data, such as vibration data, were measured along the three main axes of the work-piece. In particular, vibration data were obtained using an accelerometer sensor placed on the spindle, which were then logged using LabView SIGNAL Express Software.

The areal surface measurements were obtained using an ALICONA interferometric instrument. Two surface measurements were obtained per part resulting in 34 measurements in total. The features mea sured per part are shown in Figure 1a. This instrument records the height (z) at sampled locations (x, y) with uniform sampling and a sampling interval of 10 μm. The instrument measures the raw surface metrology data and preprocessing is needed to obtain the standardized surface metrology data. The procedure for obtaining the standardized surface metrology data is shown as follows.

1. Obtain the primary surface by the application of the S-Filter on the real surface. The S-Filter used is the Gaussian filter, and the standards recommended in the ISO 16 610-21 document [23] have been followed. For example, the wave- length of the S-filter is taken to be 15 times the sampling interval (150 μm).

2. If necessary (depending on the result obtained above), perform further surface filtering to obtain the scaled limited surface. It should be noted that this stage is entirely determined by expert knowledge.

3. Specify the evaluation area which is taken as five times the selected wavelength (750 μm).

4. Obtain the reference surface and calculate the parameters as described in Figure 3.

A sample of the areal surface metrology measurements obtained following the procedure above is shown in Figure 4.

4 PROPOSED FUZZY MODELING APPROACH

Fuzzy logic represents an extension of bivariate logic and was introduced in 1965 in Zadeh's seminal paper [24]. Since then fuzzy logic systems have found applications in a variety of domains including biomedicine [25], process control, manufacturing [26], and aerospace systems. The use of fuzzy systems in these applications offers a unique advantage of being able to model non-linear systems in an interpretable manner. The interpretability comes from the fact that a fuzzy logic system is a rule-based system, and the rules are similar to the natural language of humans. These rules also allow for the incorporation of expert knowledge, which can be valuable for the analysis of complex systems. Central to fuzzy logic systems are the fuzzy sets.

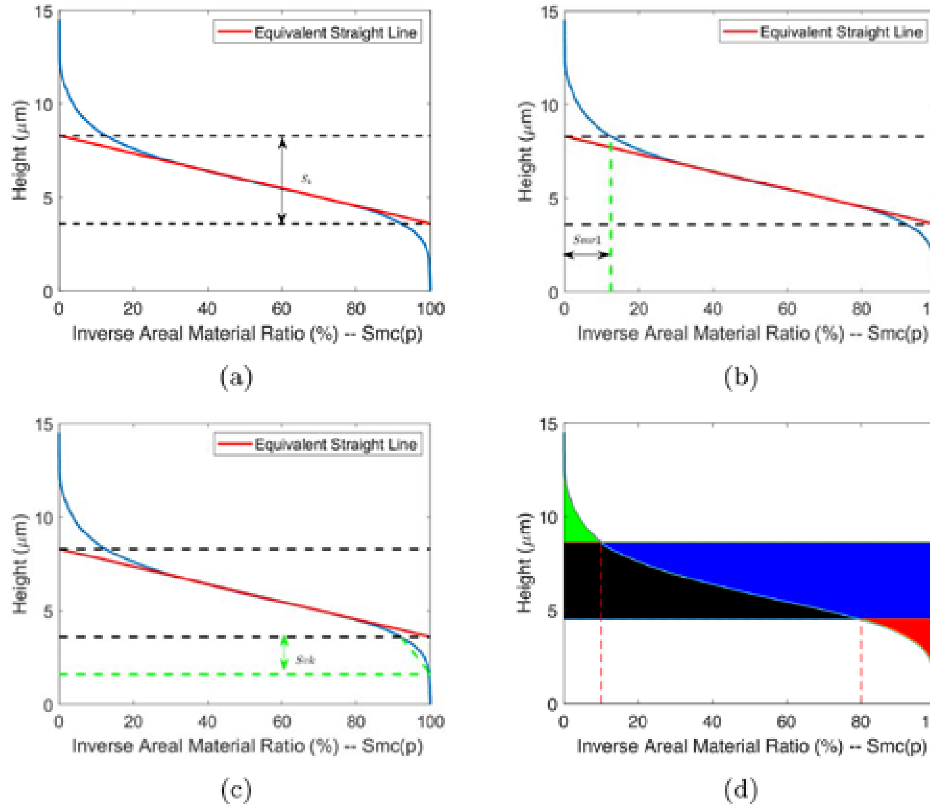

Figure 3: The process of calculating selected areal parameters. (a) Illustration of the core height (*Sk*). (b) Illustration of the material ratio at the first default point. (c) Calculation of the reduced valley height (*Svk*). (d) Important areas for calculating areal parameters: green for *Vmp*, black for *Vmc*, blue for *Vvc* and red for *Vvv*.

Fuzzy sets extend conventional sets in that they can provide to what extent an element belongs to a particular set. Mathematically, a fuzzy set (type-1), **A**, may be expressed as follows:

$$\mathbf{A} = \{x,\ \mu_{\mathbf{A}}(x) | x \in X\}$$ **Equation 1**

where $\mu_A(x)$ is the membership degree of the fuzzy set of an element x in the Universe of discourse X, $0 < \mu_A(x) < 1$. The fuzzy logic system (FLS) can be considered to be a mapping from the input space (defined as X) to the output space (defined as Y) (Figure 5). Such a mapping can be formulated by the following equation:

$$\hat{y} = \sum^{c} \phi_j(x) \lambda_j$$ **Equation 2**

where ŷ is output of the fuzzy logic system, $\phi_j(x)$ represents the degree of validity for the jth rule (for a total number of c rules) for an input $x \in R^N$. $\phi_j(x)$ represents the normalized firing strength of a particular input in each input space. The nature of λ_j is what determines if the fuzzy system is of the Mamdani or of the Takagi Sugeno Kang (TSK) type. For the Mamdani type, λ_j represents the output/consequent fuzzy set of the jth rule while for the TSK type, λ_j represents a linear function ($\lambda_j = ax + b$).

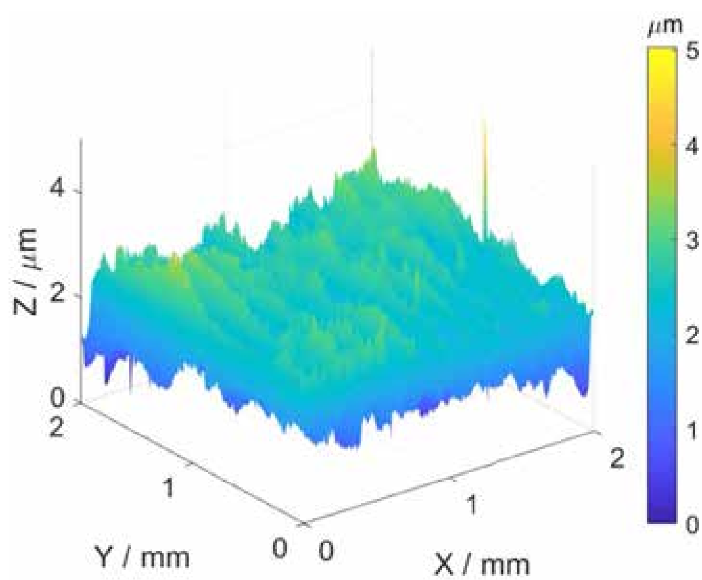

Figure 4: Surface metrology measurement of Part 1, feature B. The figure includes a 3 mm × 2.5 mm surface patch, which a sampling density along the two axis equals to 100 samples per mm. Hence sampling interval is 10 μm.

4.1 Identifying Fuzzy Models

As discussed in the preceding section, the fuzzy model can be thought of as a nonlinear interpretable mapping from the input space to the output space. The fuzzy system is parameterized (the fuzzy sets can be represented by parameters) and such parameters can be learned from the data obtained from the system to be analyzed via fuzzy logic. There exists a plethora of approaches for identifying the parameters of the fuzzy logic system such as optimization of the cost function via gradient descent and iterated re-weighted least squares [27]. As the goal of this article is to develop an approach that can generalize across the different areal parameters, it is imperative that a robust framework be found. Consequently, the proposed algorithm development follows a number of steps as discussed in the preceding sections.

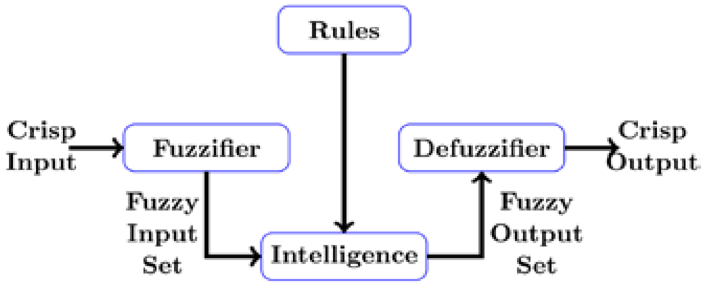

Figure 5: Fuzzy mapping block diagram.

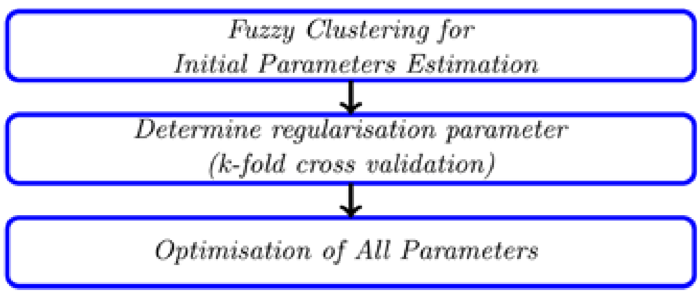

Figure 6: Block diagram of the steps involved in obtaining the fuzzy model.

4.2 Fuzzy Modeling Approach

The fuzzy model used here is of the Mamdani type because it can be shown to represent the most transparent of fuzzy models. The block diagram for the process of obtaining the fuzzy model from data is shown in Figure 6.

The first step involves the use of fuzzy c-means data clustering of the product space, which provides an initial good guess of the parameters of the fuzzy model and will later be optimized. As shown in [26], such an approach can help in preventing the optimization algorithm from being stuck in a local optima. The number of clusters determines the number of fuzzy rules in the trained fuzzy models. To determine the optimal number of fuzzy rules (which is the same as the number of clusters), a crude search was carried-out to find out the region where the optimal number fuzzy rules is. The authors found that for very large number of fuzzy rules, the algorithm overfitted on the hold-out set, and this gets progressively worse as the complexity of the model increases. The search for the optimal number of fuzzy rules was thus limited to between 2 and 12. The second step involves determining the regularization parameter. This step involves defining a cost function — a penalized root mean square error (RMSE) defined by the following equation:

$$\hat{\beta} = \arg\max_{\beta} = \underline{\|\mathbf{y} - \mathbf{f}(\mathbf{X}, \beta)\|_2^2} + \underbrace{\lambda\|\beta\|_2^2} \qquad \textbf{Equation 3}$$

where $\mathbf{f}(\mathbf{X}, \beta)$ represents the output of the fuzzy system, $\mathbf{y}$ is the vector representing the output data and λ is a penalty term that penalizes for large values of the fuzzy model parameters. The value of λ is determined via a K-fold cross validation using the following steps:

Algorithm 1: K-fold cross validation algorithm for determining the regularization term

1. Divide the training data set into K-folds. Note that there is a 70%-30% split in training data to testing data. This resulted in a training data of 24 data points. The value of K was chosen to be 4 which means there were 6 data points per fold.

2. From 10^{-2} to 10^{6} (on the log scale), select a particular λ and train the fuzzy model on the three folds and test on the remaining one fold. The approach is repeated until when all the data folds have been tested. Record the λ value and corresponding RMSE.

3. Zoom in on the λ values and find the λ values with the lowest error (RMSE) and repeat procedure 1-2 if necessary.

4. Select the fuzzy model with the lowest RMSE (without the penalty term) and record the value of λ.

It should be noted that steps 2 and 4 above involve a training procedure which involves finding the parameters, which minimize the error function as defined in Equation 3. The procedure by which this has been done in Algorithm 2 is based on the scaled conjugate gradient algorithm.

Algorithm 2: Scaled Conjugate Gradient algorithm for finding the optimal parameters

Given the objective function of Equation 3, the parameters of the fuzzy models are obtained via the scaled conjugate gradient descent algorithm. The fuzzy sets for both the antecedent and the consequent variables are assumed to be defined by Gaussian membership functions with two parameters, $\left(\mu(x) = \exp\left[-\frac{1}{2}\left(\frac{(x_j - v_j)}{\sigma_j}\right)^2\right]\right)$. v and σ correspond to the center and spread of the membership function. The output of a Mamdani fuzzy system is given by the following equation:

$$\hat{y} = \frac{\sum_{i=1}^{R} \lambda_i \prod_{j=1}^{n} \exp\left(-\frac{1}{2}\left(\frac{(x_j - v_{ij})}{\sigma_{ij}}\right)^2\right)}{\sum_{i=1}^{R} \prod_{j=1}^{n} \exp\left(-\frac{1}{2}\left(\frac{(x_j - v_{ij})}{\sigma_{ij}}\right)^2\right)} \qquad \textbf{Equation 4}$$

where x represents the jth input for a total of n inputs and c fuzzy rules. The derivative of the antecedent and consequent parameters are given by the following equation:

$$\frac{\partial e}{\partial \theta_{ij}^{l}} = (\hat{y} - y)\left(\frac{\lambda_i - \hat{y}}{\mathbf{F}^{\mathrm{T}}\mathbf{1}}\right)\left([\prod_{\substack{q=1 \\ q \neq j}}^{n} \mu_{iq}]\frac{\partial \mu_{ij}}{\theta_{ij}^{l}}\right) \qquad \textbf{Equation 5}$$

where θ^{l}_{ij} is the lth parameter of the jth antecedent of the ith rule. for $j = 1, 2, \ldots, n$, $i = 1, 2, \ldots c$, and $l = v, \sigma$. For each parameter, it can be shown that their derivatives with respect to the center and spread of the membership functions can be given by the following equations:

$$\frac{\partial \mu_{ij}}{\partial v_{ij}} = \frac{(x_j - v_{ij})\mathbf{N}(v_{ij}, \sigma_{ij}; x_j)}{\sigma_{ij}^{2}} \qquad \textbf{Equation 6}$$

$$\frac{\partial \mu_{ij}}{\partial \sigma_{ij}} = \frac{(x_j - v_{ij})^2\mathbf{N}(v_{ij}, \sigma_{ij}; x_j)}{\sigma_{ij}^{3}} \qquad \textbf{Equation 7}$$

The derivative with respect to the consequent parameter is given by the following equation:

$$\frac{\partial e}{\partial \beta_i} = (\hat{y} - y)\left(\frac{f_i}{\mathbf{F}^{\mathrm{T}}\mathbf{1}}\right) \qquad \textbf{Equation 8}$$

where β_i is the consequent parameter of the ith rule. It should be noted that $\mathbf{N}$ represents an unnormalized Gaussian function. $\mathbf{F}$ is a vector representing the firing strengths across all the rules and $\mathbf{1}$ is a vector of ones. It is worth emphasizing that the scaled gradient descent algorithm was used in this article. At iteration k, the parameters are updated as follows:

$$\mathbf{P}_k + 1 = \mathbf{P}_k + \alpha_k \mathbf{d}_k \qquad \textbf{Equation 9}$$

$\mathbf{P}$ is the vector of parameters, α is the step size, and $\mathbf{d}$ is the search direction. $\psi_k = \alpha_k \mathbf{d}_k$ is given as follows:

$$\psi_k = \frac{g_k^{|}\,\mathbf{d}_k}{\mathbf{d}_k^{\top}\mathbf{H} + \beta_k\,\|\mathbf{d}_k\|^2} \qquad \textbf{Equation 10}$$

where **H** is the Hessian that can be approximated as discussed in [27]. It is worth emphasizing that Equation 3 includes a loss function, which can be used to control the interpretability of the elicited fuzzy model. The center of sets defuzzification method was employed in this research, but the proposed approach extends easily to other defuzzification methods.

5 RESULTS

5.1 Data

The datasets used in this research study are the surface metrology data (an example is shown in Figure 4) and the process vibration data. The vibration dataset is a time series data sampled at a frequency of 10KHz. Sets of vibration data in the *x*, *y*, and *z* directions were obtained per feature in each of the parts. From the vibration data, feature extraction was performed. The features extracted included time and frequency domain features (for example mean [10], root mean square value [17] and the Fourier transform frequency components). A total of 206 features were obtained from the vibration data. A distribution of the vibration data as well as selected input features shown in Figure 7 indicates the data is sparse and multidimensional.

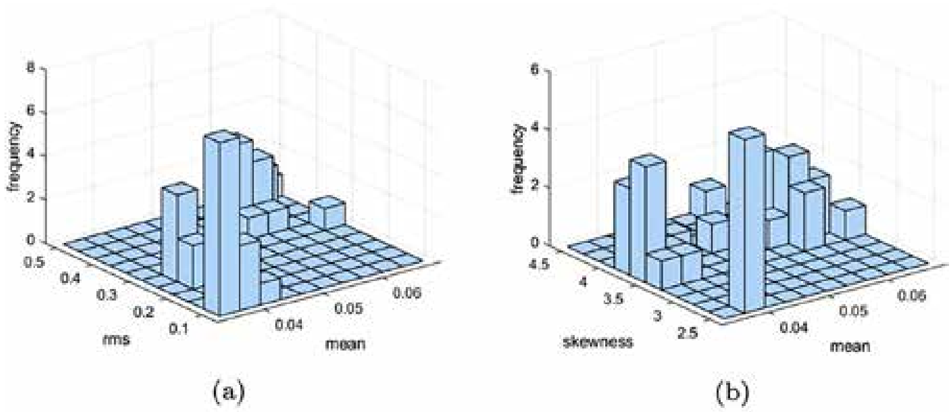

Figure 7: (a) Distribution of selected input variable's root mean square and mean (RMS) of the vibration data. (b) Distribution of selected input variable's skewness and mean of the vibration data.

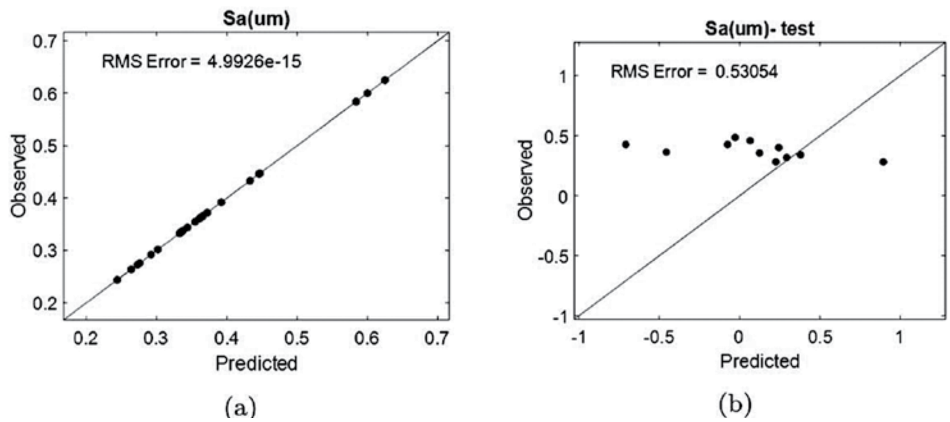

Figure 8: Linear regression performance on the training and testing data for a selected output variable (Sa). There is overfitting because the system is overdetermined.

The 24 areal parameters from the surface metrology were also obtained using an in-house software developed by the authors. The procedure for deriving the parameters are as outlined in the ISO standard as well the studies performed in [20, 28].

It is worth emphasizing that the modeling problem is challenging because of the high dimensionality and sparseness of the data points. Specifically, there are 34 data points in all (25 training data points), which points to the fact that it is easy to overfit on the training data [26]. This phenomenon is representative of many manufacturing processes (such as in the manufacture of aerospace components) where parts are manufactured in low volume. It would be interesting to investigate how the proposed approach performs in this challenging modeling problem. It should be noted that a penalized error function coupled with *K*-fold cross validation is proposed for the modelling problem as discussed in section IV. There is a 70%-30% split between training and testing data sets. This split was performed after a random sampling of the full data set.

The performance metric used for evaluating the developed models is the RMSE. The 206 features were extracted from the raw vibration data. New deep learning approaches make it possible to use raw time-series data in the modeling problem as shown in [29]. This line of thought was not pursued further because this may not be feasible for cases of low volume manufacture such as the one considered in this paper.

5.2. Linear Regression Modeling

Linear regression modeling is the work-horse of modeling in manufacturing. To test the proposed approach on other modeling problem, linear regression is chosen as a benchmark so the results obtained from the proposed approach can be compared. The linear regression modeling is given by the following equation:

$$\mathbf{y} = \mathbf{X}\beta + \epsilon \qquad \text{Equation 11}$$

where **X** represents the design matrix and β the corresponding parameters. ε represents a zero-mean Gaussian noise. For a sum of error square cost function, the solution to the optimization problem is given by the following equation:

$$\hat{\beta} = (\mathbf{X}^{\top}\mathbf{X})^{-1}\mathbf{X}^{\top}\mathbf{y} \qquad \text{Equation 12}$$

It is worth noting that, as there are significantly more features than data points, the linear regression modeling problem will be overdetermined and will result in overfitting on the modeling problem. This was indeed the case when a linear model was performed on the training data. These results are shown in Figure 8.

As can be seen from the results of Figure 8, the linear regression model fits the training data perfectly but does not generalize well to unseen data (as can be noted form the testing data set performance). To allow for better generalization to unseen data, the linear regression cost function can be penalized as given by the following equation:

$$\hat{\beta} = (\mathbf{X}^{\top}\mathbf{X} + \lambda\mathbf{I})^{-1}\mathbf{X}^{\top}\mathbf{y} \qquad \text{Equation 13}$$

where λ is called the ridge parameter whose function is to penalize for large weights. As already mentioned, the penalty term (λ was determined by *K*-fold cross validation) as described in Section 3. The penalized linear regression (ridge linear regression) results is as shown in Figure 9.

As can be seen from Figure 9, although the results of the testing

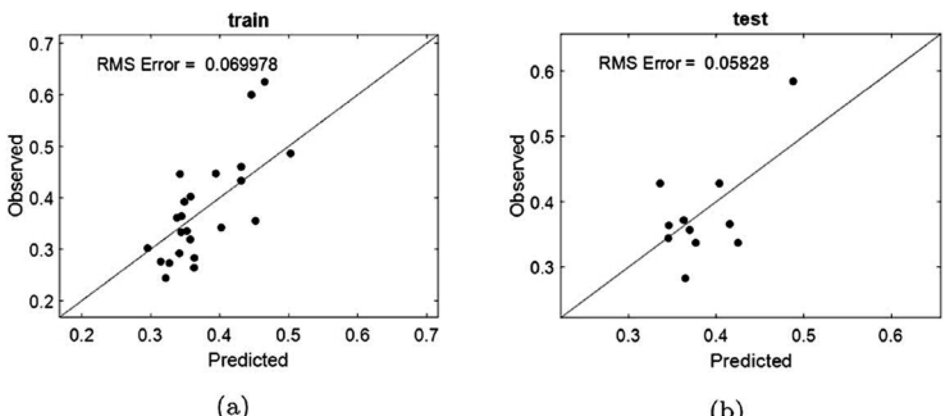

Figure 9: Penalized linear regression results.

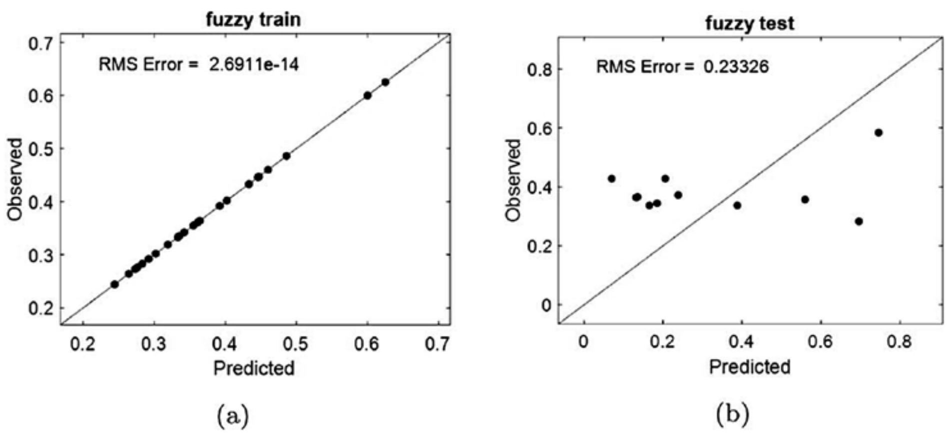

Figure 10: Mamdani-based fuzzy logic modeling results.

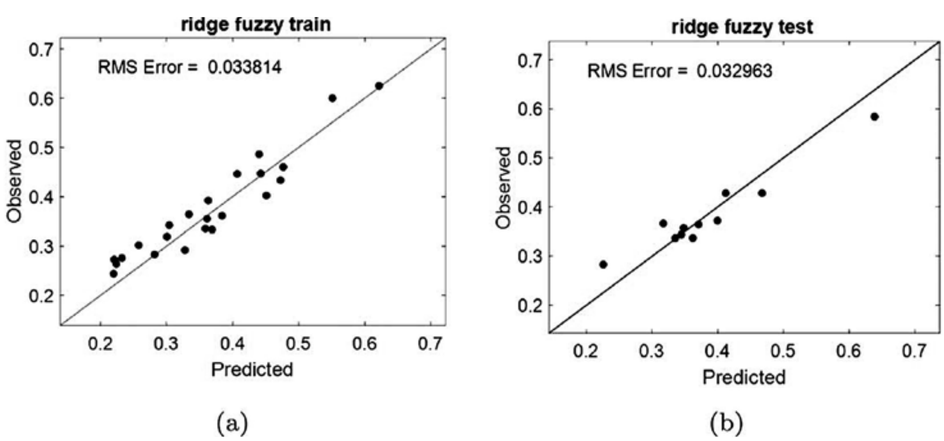

Figure 11: Ridge Fuzzy Modeling results.

datasets are more generalizing when compared with ordinary linear regression results, the training data set is significantly much worse. This is as a result of the fact that the ridge parameter is able to find a compromise between the best training results (in the linear sense) and the best validation results (in the linear sense). The results suggest that a non-linear model is required to obtain a good mapping of the process parameters. It is for this reason that the Mamdani fuzzy model is first considered as discussed in Section 3. The first Mamdani model considered is not inclusive of any penalty term that has already been explained can result in overfitting of the training model. Such a result is similar to the ordinary regression result (shown in Figure 8). The fuzzy modeling result without any penalty term is shown in Figure 10.

To allow for better generalization, the same ridge linear regression training procedure (discussed in Section 4) is also followed to train the Mamdani fuzzy model. The results of the ridge Mamdani fuzzy system is shown in Figure 11. We have called this approach the ridge Mamdani fuzzy modelling approach to emphasize its capability to penalize for large fuzzy weights in order to improve generalization performance.

As can be seen in Figure 11, the ridge fuzzy modeling framework provides a much-improved performance and is able to map the process features to the surface metrology parameters. The result shown in Figure 11 can be replicated across all the other areal surface metrology parameter, which indicates the proposed modeling methodology predicts with accuracy regardless of the parameter of interest. Tables 3 and 4 respectively show the performances of the linear/ridge regression method and the proposed fuzzy approach in predicting 24 areal parameters. The results from these tables indicate the proposed approach is able to generalize across different areal parameters and provides consistent as well as robust modelling results.

As can be observed from Tables 3 and 4, for the ordinary linear and fuzzy models (without penalizing the weights), the models overfit significantly on the training data set and perform badly on the testing data set across all the 24 areal parameters. The training error is close to zero and this fact is corroborated by Figures 8 and 10. For ridge linear and fuzzy models, the results are better (improved modeling accuracy on the test data). For example, if one considers the Sa para- meter in the two tables mentioned, it can be seen that the training RMSE for both the ordinary linear and fuzzy models are negligible (2e-15 and 3e-15 respectively). The testing performance is respectively 0.531 and 0.233. Although the fuzzy model is better than the lin- ear regression approach (for the ordinary model), there is overfitting on the training data set. The performance is much improved when using the proposed ridge approach. For example, the ridge ordinary fuzzy model has a training RMSE of 0.034 and a testing RMSE of 0.033 (shown in Figure 11). The ridge approach is able to provide a balance in the accuracy of training and testing results.

It should be noted that using the ridge approach on the testing data set, the fuzzy model is able to provide improvement on the modeling accuracy as compared to the linear modeling approach by approximately 75%.

6. CONCLUSION

This article has presented a new framework based on the ridge Mamdani fuzzy logic system for the mapping of process features to areal surface metrology parameters. The proposed approach represents a non-linear but interpretable solution to the manufacturing

Output	Linear Model			
	Training (RMSE)		Testing (RMSE)	
	ORDINARY	RIDGED	ORDINARY	RIDGED
Sa (µm)	2e-15	0.070	0.531	0.058
S5z (µm)	9e-14	5.62	15.47	6.97
Std (deg)	1.7e-13	9.53	82.97	29.87
Smr2 (%)	3.5e-14	1.72	7.57	2.04
Smr1 (%)	1.6e-13	3.29	11.26	2.06
Svk (µm)	7.52e-14	0.236	1.013	0.124
Sk (µm)	9.38e-13	2.938	19.16	2.963
Spk (µm)	5.87e-14	0.357	0.907	0.426
Vvv ($\mu m^3/mm^2$)	3.99e-09	24148	183896	45 020
Vvc ($\mu m^3/mm^2$)	4.13e-08	200 705	803476	165 007
Vmc ($\mu m^3/mm^2$)	2.56e-08	108 141	342 019	83579
Vmp ($\mu m^3/mm^2$)	2.56e-09	20378	87845	26271
Sdr (%)	7.88e-15	0.0514	0.32129	0.033 43
Ssc (1/µm)	5.05e-16	0.00137	0.009 20	0.000 92
Sdq	3.27e-15	0.01	0.06993	0.00757
Sal (mm)	3.68e-15	0.0246	0.0712	0.0361
Str	1.07e-14	0.1842	0.30599	0.1697
Sds ($1/mm^2$)	5.42e-11	80.319	342	84.70
Sz (µm)	8.42e-13	7.1029	43.5086	8.7398
Sv (µm)	6.13-13	6.0068	58.2909	4.6297
Sp (µm)	2.93e-13	3.2261	20.5911	7.7376
Sku	4.20e-12	93.103	468.96	75.193
Ssk	1.34e-13	3.7123	33.302	4.8714
Sq (µm)	3.98e-14	0.1708	1.0248	0.1431

Table 3: Linear model results in predicting 24 areal parameter values.

Output	Fuzzy Model			
	Training (RMSE)		Testing (RMSE)	
	ORDINARY	RIDGED	ORDINARY	RIDGED
Sa (µm)	3e-15	0.034	0.233	0.033
S5z (µm)	11e-14	2.98	17.21	3.24
Std (deg)	1.8e-15	12.13	93.07 1	3.80
Smr2 (%)	3.5e-14	1.34	6.54	1.86
Smr1 (%)	6.8e-14	2.12	12.08	2.86
Svk (µm)	2.88e-15	0.227314	0.72936	0.0409
Sk (µm)	13.59e-14	2.828	1.801	1.937
Spk (µm)	2.25e-15	0.343353	0.653594	0.1401
Vvv ($\mu m^3/mm^2$)	1.53e-10	23243.37	132405	14780.19
Vvc ($\mu\mu m^3/mm^2$)	1.58e-09	193179.4	578503	54171.99
Vmc ($\mu m^3/mm^2$)	9.82e-10	104085.7	246254.1	27439.17
Vmp ($\mu m^3/mm^2$)	9.82e-11	19614.5	63249.06	25914.31
Sdr (%)	3.02e-16	0.0494	0.2313	0.0329
Ssc (1/µm)	1.94e-17	0.001323	0.00662	0.000908
Sdq	1.25e-16	0.009992	0.05035	0.007471
Sal (mm)	1.41e-16	0.023636	0.0044	0.0355
Str	4.11e-16	0.177273	0.0190	0.167451
Sds ($1/mm^2$)	2.08e-12	77.307	21.256 1	9.482
Sz (µm)	3.22e-14	6.8365	2.7018	2.010
Sv (µm)	2.35e-14	5.785	3.6198	1.0648
Sp (µm)	1.12e-14	3.101	1.2787	1.7796
Sku	1.61e-13	89.61	29.122	17.294
Ssk	5.13e-15	3.573	2.0680	1.1204
Sq (µm)	1.52e-15	0.1644	0.06364	0.0329

Table 4: Fuzzy model results in predicting 24 areal parameter values.

informatics modeling problem. The main contribution of this article is the development of a modeling solution that provides consistent accuracy across all the 24 areal parameters on which the results were tested. This is the first time such a framework has been validated across different areal parameters even in the face of a challenging, nonlinear, sparse, multi-dimensional modeling task. In particular, the validation results of the proposed strategy contrast existing areal parameters modeling methods where either results do not generalize across many areal parameters or validation results are difficult to obtain. The proposed approach may benefit from adding an extra layer of inherent in manufacturing systems can be adequately modeled as well as understood. This will be the main focus of future research studies.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available upon reasonable request from the authors.

ETHICAL APPROVAL

Not Applicable.

CONSENT TO PARTICIPATE

Not Applicable.

CONSENT TO PUBLISH

Not Applicable.

AUTHORS' CONTRIBUTIONS

Olusayo Obajemu analyzed the datasets and carried out the computer simulation experiments. Moschos Papananias and Thomas E. McLeay designed the laboratory experiments and architected the data acquisition/processing pipeline. Mahdi Mahfouf and Visakan Kadirkamanathan provided technical guidance and validation of the experiments/algorithms developed in the study.

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COMPETING INTERESTS

The authors have no conflicts of interest to declare that are relevant to the content of this article.

AVAILABILITY OF DATA AND MATERIALS

Not Applicable.

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WOMEN IN MANUFACTURING: DIVERSIFYING THE INDUSTRY

The presence of women in manufacturing will continue to grow as more opportunities manifest themselves early on, including education and mentorships.

By KENNETH CARTER, Thermal Processing editor

You don't have to go very far back in time to find a point where the role of women in the manufacturing sector was practically nonexistent. But over the last decade or so, the ratio of women to men has seen a dramatic increase, although those statistics still have much room for improvement.

Diversity in any industry is always a good thing, but in an area that has been — until recently — traditionally dominated by men, an influx of women who can offer different perspectives can only be a boon to a company's innovation, as well as its bottom line.

With the dynamics and environment within manufacturing companies changing, it becomes even more imperative that young girls who express an interest in the field be given every opportunity to allow that spark to grow.

"I've worked in several industries during my career, and while some have a lot of women employed in their businesses, there is still very much a good ol' boy network," said Lori Brown, sales manager for IMT Forge. Brown has been entrenched in the world of manufacturing solutions for aerospace, defense, and industrial markets for the last 12 years. "For example, I worked in sport education for my previous job. When you deal with football or baseball coaches, they don't like a female training them on how to coach kids, whereas I didn't notice that as much when I came on board IMT Forge. I would say in our office, which we probably have at any given time anywhere from 40 to 50 office personnel, that about 10 percent of the office was women when I started 12 years ago. Today, it's probably 70 percent women — and they're in leadership roles."

That shift is also showing up in higher education, which can often lead to a prominent position in manufacturing.

"Even in the last 10 years, I would say that women definitely have a more apparent presence, but they're still vastly underrepresented compared to how many men are in the field," said Corinna Draghi, applications and design engineer with Atlanta Gear Works. "That is something that honestly will just take time. Something that I have noticed is that STEM in general, science, technology, engineering, math, all that stuff, is pushed a lot more toward the girls in schools from an early age. At Georgia Tech — where I was a freshman years ago — our ratio of men to women was approximately one woman for 10 men on campus. It was outrageously backwards. I think now it's more like one to three, so the numbers have gotten better, but that's not to say they're all in manufacturing. We still have a long way to go in terms of women in manufacturing specifically. There are not enough of us. And the ones that I do see on the shop floors, when I go to the plants, a lot of the times, they're not the ones getting dirty."

MAKING OPPORTUNITIES KNOWN

But as more opportunities manifest themselves early on, that can only mean the presence of women in manufacturing will continue to grow. But much of that growth is dependent on bringing those opportunities for women front and center.

"One way you can do that is by looking at your benefits: What it is that women need? What kind of support do they need? What's going to attract them to the workforce? And it could be a variety of things," said Veronica Lancaster, vice president of standards programs in the Technology & Standards Department of the Consumer Technology Association. CTA™ is North America's largest technology trade association, which helps support more than 18 million U.S. jobs. "It doesn't have to be your traditional healthcare, although that's very important. It could be more personal time that you need — depending on your job in the manufacturing industry, obviously. It's hard to work from home if you need to be on the floor, but you could modify your hours. You could allow for early starts and later starts, bringing more flexibility."

IMPORTANCE OF MENTORING

Lancaster also points out the importance of mentoring programs.

"It is valuable to bring together women in your organization," she said. "If you have someone who has been there for a while, pair them up with a newcomer. This also creates meaningful opportunities for reverse mentoring. If you have someone more experienced who can teach a new professional, chances are they are going to teach something in reverse as well. It's a valuable relationship."

That mentoring program can also be a useful tool in college as well, according to Draghi.

"If more women could find a mentor, someone in the field who could help them kind of get there faster, to be a filter through all of the other noise to help figure things out, that would help a lot," she said.

Brown, Lancaster, and Draghi took part in a recent panel on Women in Manufacturing at the Motion+Power Technology Expo in St. Louis, Missouri, in September. During the panel discussion, they talked about the importance of women in the manufacturing sector and what it could mean to a company's performance.

"What do we do about that? I mean, diversity, equity, and inclusion are obviously some of the areas that you should focus on, and each industry has different challenges," Lancaster said. "But some of the things that I learned as a panelist had to do more with some leaders not understanding, 'How do we do this exactly? How do we target in this sector?'"

VARYING WAYS TO RECRUITMENT

The good news is there are multiple avenues in which companies can explore to recruit more women.

"Companies can take a look at how they do things and how they might participate," Lancaster said. "If there's a fixed sector of the manufacturing company that is predominantly male, they might offer incentives to recruit women on staff and then pair them with someone that can be more of a partner. Sometimes, when you think about those old boys' clubs, it can be intimidating. So, having that freedom to feel like you can speak up, offer your expertise, guidance,

Anecdotally, women's roles in manufacturing are becoming more commonplace, but the journey to get there can still be a challenge to navigate. (Courtesy: Shutterstock)

and having a partner on the floor can inspire confidence."

New personalities can often lead to personality conflicts, but Draghi said that many times that potential conflict might never exist in reality.

"It's kind of weird because, when I first started, I honestly was less weirded out by it than the guys were. They were like, I know it's weird but, 'There's a chick here.' And I'm like, 'Yes. Hi.' Once they get to the point where they know you know what you're doing, you're just one of the guys," she said. "And I'm honestly fine with that. I don't really necessarily mind it being a men's club because there's not really any exclusion there. They don't prevent me from being part of things. I go to lunch with them; I hang out with them. Some of the guys here actually have invited me to things with their family. So, there is inclusion, but I think a big thing for them in their 'men's club' is you have to know what you're doing. If you cannot prove you know what you're doing, if you cannot prove you're capable and competent, then they don't have anything to do with you — guy or girl."

A TRICKY JOURNEY

Anecdotally, women's roles in manufacturing are becoming more commonplace, but the journey to get there can still be a challenge to navigate, according to Lancaster.

"Expecting diversity and looking for ways to make sure you're integrating women can be tricky as well," she said. "I think if you are going to offer benefits or signing bonuses or something else to try to diversify your workforce, that could cause some friction on the other side. It has to be handled carefully."

Sometimes that can be as simple as building on what is already there, according to Lancaster.

"From my perspective, both in standards and technology, I see that changing," she said. "What I've found, and some of this has happened organically for me speaking on the standards side, when I first started 25 years ago in telecom — some areas had women involved, like ordering, billing, things like that. But once you got more in depth into some of the networking or timing and synchronization, that was very male heavy. What I tended to do was gravitate toward the other women who were there. We could talk together about the problems that we were having — whether it's not feeling like you have a voice or not feeling like we have a lot of allies. And slowly those networks grew."

"I think there are tons of areas that women can contribute in manufacturing, but what I think we are lacking most is attracting younger people. I don't think companies have evolved to really show the younger generation how awesome this industry can be."

MORE THAN JUST A GENDER ISSUE

There are many additional issues that often manifest beyond gender, Lancaster said. Those can include different nationalities, different religions, or different comfort levels.

"Even in business, you have different roles," she said. "Some roles in

China and Japan, for example, are more male dominated by tradition, and it's tough for women to break into those roles. But I'm starting to see some change with women in traditionally male roles. In one group that I'm in, the head of the delegation from China is a woman, and that's highly unusual. So, we're seeing more change, and I think that is encouraging."

Emotional differences can also be an issue, but they don't necessarily have to be a detriment, according to Brown.

"Definitely women are more emotional, and you heard that from other panelists; I struggle with being overly emotional myself," she said. "I do feel like we do see a lot more outward strength from male leaders, but if they're smart guys — and I do work, luckily, around a lot of smart men — I think they're open to good ideas. If you have a business case, and you stand your ground, and you put forward thoughtful, factual information, they're going to go with your idea. And if I start crying in a meeting, that's usually when I get told 'no.' There's no crying in forging after all."

COMPANIES SEEING THE POSITIVES

Draghi pointed out that conservative companies — and the manufacturing world is full of conservative companies — are more willing to hire women in a huge push for global inclusion simply because these companies have come to the realization that women process things differently than men, and that can be advantageous.

"And vice versa — I'll see things that the guys don't see; they'll see things that I don't see," she said. "I'm one of three job engineers, and I'm the only female. My boss is also a male. So, they're seeing, as I've been here, that I can handle myself on the floor, and I also see things differently than they do, or I'll catch some more detail-oriented things. I see the push for just women in general, and I guess I never really noticed the lopsidedness of it. I never really thought that women didn't have as much opportunity because my dad was the reason that I got into manufacturing. He was like, 'If you want to do it, you can do it. You're good at math. Go for it.' There was never a question, but I was lucky in that aspect. Not everyone has that."

LABOR FORCE: BY THE NUMBERS*

57.4 Percent of all women who participated in the labor force.

57.1 Percentage increase from 2018.

69.2 Percentage of labor work force for men.

3.6 Unemployment rate for women (down 0.2 percentage points from 2018).

3.7 Unemployment rate for men (down 0.2 percentage points from 2018).

45 Percentage of women ages 25-64 with a bachelor's degree or higher, compared with 11% in 1970.

51.8 Percentage of women amongst all workers employed in management, professional, and related occupations.

$821 Average weekly earnings among women working full time.

$1,025 Average weekly earnings among men working full time.

1.1 million Number of female veterans in the labor force.

3.9 Median number of years employed women were with their employers (January 2020).

*Unless indicated, all statistics are from 2019.

Source: U.S. Bureau of Labor Statistics

DISMANTLING STEREOTYPES

Companies are also rethinking whether women should be on the shop floor because of the cliché that women may be too sensitive and can't handle the environment, according to Draghi.

"That's not always the case, and I'm a prime example of that," she said. "I am probably one of the least sensitive women you'll ever meet, and that's why I can handle it. And (companies) are realizing that you need to interview everybody, meet them in person, talk to them, see what their personality is. And one of the big things that our company did when I was hired was a personality profile. And I think that is something that would massively help other companies that are struggling to add women to their workforce. It would definitely help everyone to see, 'OK, there are some women that line up with these men in terms of personality, and they will mesh with our company well.' And I think that is a big factor. If more people did that, they would see a difference when they interviewed those women. Honestly, most of the companies that I've seen that are willing to hire, and are actively hiring, women in manufacturing already do it. I think that's a big thing."

Despite some challenges, Brown said there are a plethora of opportunities for women who want to be a part of the manufacturing world.

"I think there are tons of areas that women can contribute in manufacturing, but what I think we are lacking most is attracting younger people," she said. "I don't think companies have evolved to really show the younger generation how awesome this industry can be. You don't need an engineering degree, but you do need to have critical thinking skills. My daughter's 28, and she's a wonderful, bright, creative person. But when she came to my job, she said, 'This place is scary. It's like going to the depths of hell.' You're dealing with steel, and you've got metal shavings, and you hear this pounding all day long. It's a little intimidating. Our building shakes where I work, because we make big parts, and we're constantly banging them out."

Brown said IMT Forge's current production manager, who is a woman, started as a customer service representative.

"She's a very strategic thinker, and she has moved her way up, now managing at least four different disciplines in our company," she said. "No doubt she's one of the key leaders in our facility and has really helped us improve in so many ways. So, how do we get more people like her? I recruited her because I just saw her spunk. I knew her personally, but she would've never thought to apply. She didn't even know what a forger was. When I talked to several people at the Motion+Power Tech conference, I heard a lot of folks say, 'It's not even enough going to the colleges to recruit younger people, because that's too little, too late.' We need to get these kids when they're in high school. And definitely I think when you have a mix of men and women, young and old on a team, you're going to be more successful because we are different."

REACHING OUT AT THE HIGH SCHOOL LEVEL

Lancaster also agreed that it is important to approach girls while they're still in high school and let them know the possible career paths that manufacturing can offer.

"In the panel that we were on, there was a question from the audience, and a gentleman asked about mentoring and a science club that he was involved in," she said. "That hit home for me. One issue that you see, especially in jobs like mine geared toward engineering, is you really focus on STEM. I would say manufacturers that are sponsoring STEM education should get more involved with kids and create women's or girls' STEM clubs. If you're able to create girl-focused STEM clubs that provide an environment where girls feel comfortable to speak and don't feel under pressure, that is going to help create confidence."

That can also circle back to mentoring, according to Lancaster.

"If you see a really talented young woman in your program, work with her," she said. "Help her and mentor her. You might be inspiring the next engineer that's going to come work for your company. Those same companies can create college sponsorships or college scholarships, which help women advance, then continue guiding them through their college careers."

GETTING MORE WOMEN ON THE SHOP FLOOR

Beyond that, the women who are already working "in the trenches" of a shop floor are wanting to see even more women join their ranks, and Draghi said companies are willing to take that chance more now than they have in the past.

Despite some challenges, there are a plethora of opportunities for women who want to be a part of the manufacturing world. (Courtesy: Shutterstock)

> *"If you see a really talented young woman in your program, work with her. Help her and mentor her. You might be inspiring the next engineer that's going to come work for your company. Those same companies can create college sponsorships or college scholarships, which help women advance."*

"I mean, the worst that it's going to do is you'll spend a little time training them and realize it doesn't work out," she said. "From what I've seen, it can work out, but you will never know if you do not try. I do have a few women friends from Georgia Tech: One of them was working on electric motors for a while on a shop floor as a project engineer. Another one of them did electrical engineering, and another one does a lot of software engineering. But there are still companies that are pushing for that. And I think that they're trying it; it's not necessarily going as fast as they want. You're not going to hire 10 women right away. It's going to be like a one off: one here, one there."

A surprising obstacle that many women looking for manufacturing jobs may face is that some companies just aren't tuned in to the need to diversify their workforce at all, according to Draghi.

"You don't want to have to force them to make the extra effort to try because then you feel like you're forcing something on them, but at the same time it might be completely unintentional that they are not actively hiring women. The companies may just not realize it," she said. "They're just not looking at those applicants, or they're not getting them because they're not advertising, 'Hey, we want women in our workforce.'"

FEAR OF REJECTION

But a far more personal obstacle can be fear of rejection that keeps women from applying for a manufacturing job in the first place, according to Draghi, where they may assume a company is not looking to actively add diversity to its workforce.

"Get rejected, move on, try again — that's my opinion, but not everyone sees it that way," she said. "And there are so many people that have that innate fear of rejection, and they're so worried about someone telling them no, that they just won't try. If I was that terrified of it, I never would've ended up where I am. You cannot grow. You cannot become a better engineer or employee in general, if you don't have some type of rejection or failure, or if you're not told no. You cannot learn what you're supposed to learn. You cannot grow in your professional career without that there because, otherwise, you're going to stay the same forever; nothing's ever going to change, and you're not going to see things differently or understand your mistakes."

But when companies open their doors to more women joining their organizations, it can also open up new and innovative ideas and opportunities, according to Lancaster.

"I think what you'll start to see is diversity in opinion, diversity in work style, and maybe just overall change in how you may address certain things," she said. "And it could be that you're seeing more entry level women coming in. You're seeing women on different executive paths, more training. And as you're seeing all of these three come together, you're going to see that diversity of opinion. So, where you may have had a very male, 'we're here to work,' strict kind of a perspective, you may get a better understanding of, 'Yeah, well, we're here to work, but we're also here to build a future.'"

But to get companies to that point, you have to recruit the best applicants — men or women, and a more diverse team equals a more productive team, according to Brown.

"That's just a real fact with no gray," she said. "We're very different. We're not the same. But we each have strengths, and when you put all of those wonderful skill sets on a team: You need somebody to be passionate about the customer; you need somebody to be very diligent on the operations side. That balance is important, and studies have proven that when you have a mixed team, you're going to be more successful as an organization."

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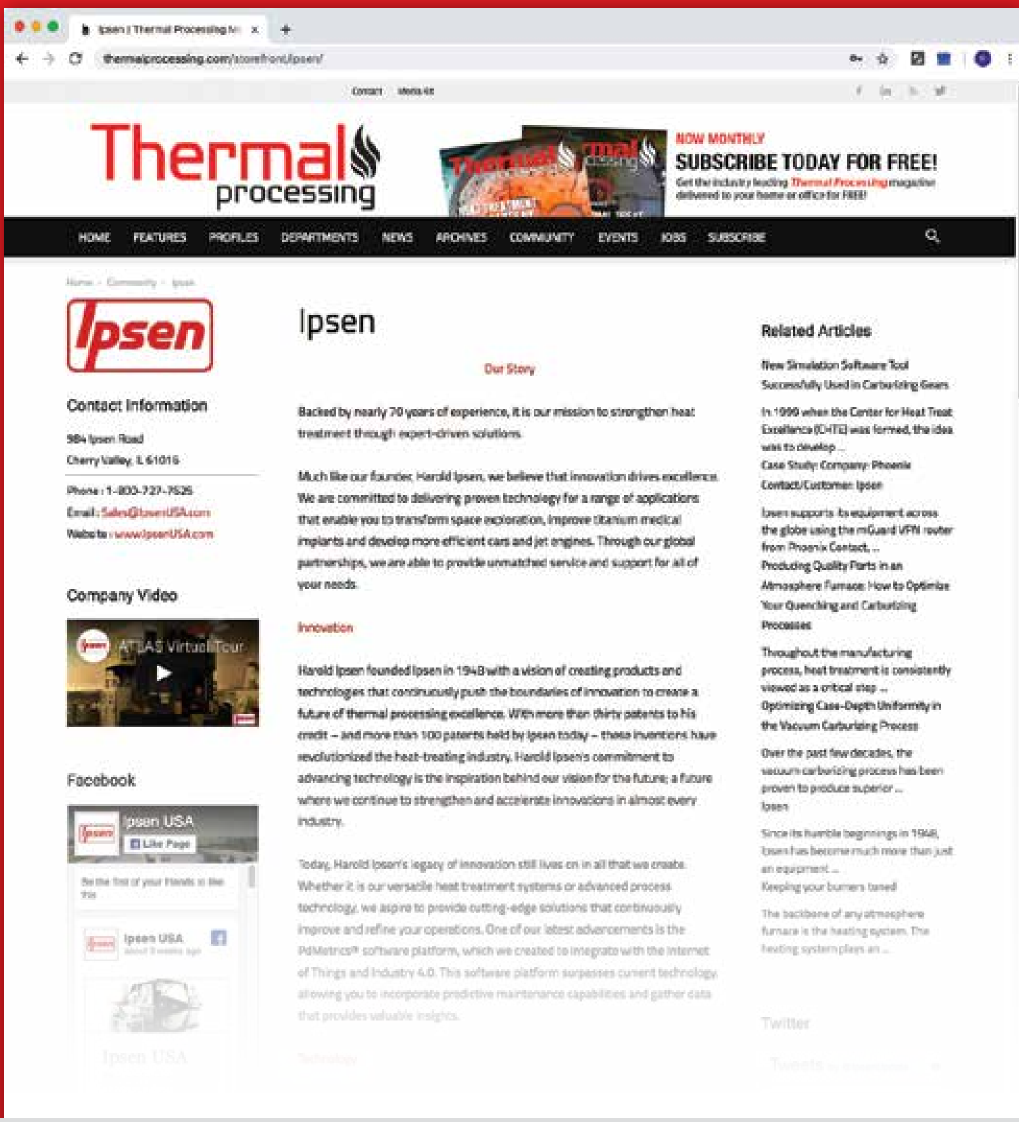

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CUSTOMIZING INFRARED HEATING SOLUTIONS

A 2-zone medium wave IR continuous food processing oven used for cheese fusing. It has source temperatures up to 1,100°F with a stainless steel construction and an independent detachable conveyor designed for cleaning. (Courtesy: INTEK)

INTEK Corp. designs and manufactures infrared ovens that deliver more precise heat application, greater speed, and superior control over key industrial heat-treatment processes.

By THERMAL PROCESSING STAFF

What manufacturing process today does not require the application of heat? From pre-heating, drying, curing, thermoforming, annealing, potting, and more, almost every product created requires heat at some point.

Heating applications run almost the entire gamut of applications, especially in industrial settings such as the ones responsible for finishing and repairing aircraft parts, annealing metal and plastic products to increase their ductility, potting (encapsulating) electronic components, preheating corrugated metal, warming and thawing pharmaceuticals, welding and vacuum-forming plastic, textile finishing, and curing.

"Almost everything that is built or sold requires heating somewhere along the line," said Jesse Stricker, founder of INTEK Corp., a manufacturer that specializes in designing and building electric infrared heating elements along with industrial ovens into which they are placed. "Ultimately the application of heat translates into making a better product — whether that involves strengthening metals and plastics so they are more durable, softening material so it can be properly formed or manipulated, or speeding the curing process to increase production."

INTEK — based in Union, Missouri — represents the modern trend toward engineering efficient and precise infrared heating systems that are quickly supplanting conventional gas and electric convection ovens as the go-to choice for this important step in manufacturing.

The company offers everything from custom heating elements, standard and custom industrial ovens (including refurbished ovens), conveyor ovens, and even industrial space heaters. Although Intek can design and build an oven using any heat source (gas/ electric), the company stands out most in its application of infrared heating elements.

For Stricker, this is more than an area of specialization, it is about the benefits and cost savings that infrared can deliver to manufacturers.

"Because an infrared heater has no moving parts and radiates so effectively, it consumes far less energy than a conventional convection oven, which requires a fan and blower," he said. "Infrared elements can even be retrofitted to conventional gas and electric ovens for further cost-effectiveness. One customer saved close to $100,000 because, instead of replacing their entire gas oven, they chose to install electric infrared heating elements designed to fit their application."

According to Stricker, most customers initially look at "standard" ovens but end up with a solution customized to fit their specific needs. Such was the case for Cooper Standard, headquartered in Novi, Michigan, a leading global supplier of systems and components for the automotive industry.

"Today, we use the infrared heating after our injection molding press that makes appliqués for automobile exteriors," said Jim Anderson, engineering manager at Cooper Standard's Rockford, Tennessee, plant. "We used to do our batch annealing in a gas oven, but that was a two-hour process."

Like many other manufacturers, Anderson's plant discovered that INTEK's infrared approach surpassed gas and electric convection heating by way of its proven precision, speed, and energy savings.

A 4-zone medium wave IR continuous oven with source temperatures of 1,100°F and Allen Bradley PLC controls. (Courtesy: INTEK)

Aside from these advantages of using infrared for industrial process heating, the economic benefits seem to tip the scales even further toward that option.

"We worked with Stricker at INTEK to design an oven to meet our product needs, bringing that particular step from hours (using the batch ovens] down to minutes," Anderson said.

LOWER PRODUCTION COSTS

Given that heating plays such an important role, the switch to infrared ovens yields substantial savings for any manufacturer from reduced energy bills and reduced floor space requirements.

Convection batch ovens transfer heat indirectly by heating moving air and hence requiring fans or blowers, which, in many situations, allow for wasted energy that is lost in the process. Additional losses stem from the requirement for heating the entire oven, even for small parts.

In contrast, electric infrared heating elements transfer energy

A 2-zone continuous dual-pass independent conveyor oven designed for preheat and cure of electric motor components. It has a process temperature of 450°F, digital heat ramp and soak controller, and adjustable index timers. (Courtesy: INTEK)

directly to the substrate of surface area via electromagnetic radiation and thus, can operate in a vacuum and never come into contact with a part or material — all while generating temperatures approaching 1,000 degrees F or more.

"People assume that gas is the cheapest way to heat, but that's not necessarily the case," Stricker said. "When considering cost, it is important to include all costs: equipment purchase price, energy cost, installation cost, floor space required, maintenance cost, etc."

On the other hand, electrically-heated infrared elements yield as much as 86 percent of their input as radiant energy that strikes the surface of a product, according to the 2008 edition of the *Heating, Ventilating, and Air-Conditioning Systems and Equipment Handbook*. Some designs may be as high as 95 percent in the form of useable heat, with the balance being lost through the power supply lines.

"Duty cycle also factors into efficiency," Stricker said. "For instance, if you buy a 70 kW conventional convection oven that operates at 75 percent duty cycle and assume, for example, a 10 cents per kilowatt-hour energy consumption, that comes to $5.50 an hour. Whereas, an infrared oven generally runs at a 40 percent duty cycle, so heating cost would drop to $2.80 per hour in this scenario."

GREATER CONTROL

Since the amount of infrared energy varies at each wavelength, manufacturers can adjust the wavelength of electric infrared heaters to match the heat requirements of a given substrate in the oven for optimum performance and control. Infrared heating also offers very fast response times, which is beneficial when holding precise temperature uniformity.

"We are finding that one of the main reasons engineers come to us for an infrared solution is that this technology can be customized to provide exacting control for any particular product," Stricker said. "Every foot in a conveyor oven path can be zoned for maximum, continuous process heating efficiency, monitored by a thermocouple in each zone."

MORE FLEXIBILITY

If anything sets Stricker and his team of engineers apart, it's their ability to take advantage of one of infrared's most useful characteristics: its adaptability. Whether used in batch ovens, walk-in ovens. or conveyor systems, infrared can apply.

"We made our name through our ability to apply infrared technology to a broad range of industrial applications." he said. "So, a plant manager can come to us, have us check out their gas or electric ovens, then we go back to our plant to design and build an entire oven system or, as a cost advantage, provide patented modular infrared replacement units for existing ovens, which may still just need a performance upgrade. The customer participates in the design and then selects the solution. This can save tons of money."

Electric infrared heater modules — typically in 12"x24", 12"x36", or 12"x48" sizes — become structural members of the oven. They can be designed to work individually for small areas, ganged together for larger areas, or even ceiling hung or wall mounted.

"Because almost every process requires heating or drying at some point, we're keeping very busy these days building our patented custom infrared ovens, modular heaters, and elements," Stricker said.

Quite a success story for an operation that started small in 1996, but one that grew quickly as a result of the ever-present demand for heating and the advantages and benefits of infrared heating technology.

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LAUREN JONES /// MARKETING PROJECT LEAD /// IPSEN USA

"We have found that whether you are an experienced or novice furnace operator, there is always something to learn or get better at, which is why Ipsen offers programs like Ipsen U."

Why is it important to invest in the future of heat-treating?

Nearly every metal component undergoes some type of heat-treating application. Vacuum furnaces contribute to the improvement of important products such as dental tools, medical devices, and components that help us build better airplanes and cars. As the consumers drive expectations, we are driven to make sure we are pushing the performance of our furnaces, resulting in better products and components in those markets we serve. Manufacturing continually gets smarter and, hence, so does heat treating — whether it be by way of automation or IIoT or simply an increase in production output. Consumer expectations are ever present and so are their heat-treating needs, so it is critical we invest in the future of both.

What role does education serve in bridging the workforce gap in the heat-treating industry?

We oftentimes work with general managers, operators, and technicians who have been heat treaters for decades, sometimes growing up in the family business. These situations are ideal because there are many foundational topics, such as metallurgy, furnace operation, recipe building, quality testing, and maintenance-best practices, which can be learned over time. On the contrary, some of our customers are purchasing a vacuum furnace for the first time, so that baseline of knowledge is critical. Over the years, we have found that whether you are an experienced or novice furnace operator, there is always something to learn or get better at, which is why Ipsen offers programs like Ipsen U.

How is Ipsen attracting the next generation of heat treaters?

Ipsen provides a couple of programs to attract and retain our technical resources. By maintaining a positive reputation of being a premier vacuum furnace manufacturer, those already in heat-treating know our credibility. However, when we look outside of the heat-treat world and at new graduates, this talent may not understand what we do. That is where resources such as the Ipsen Corporate Academy (internal) and partnerships with associations such as MTI's Educational Foundation (external) help us. We find people who are skilled and willing to learn, and then train them on all-things-Ipsen.

What types of programs are available, and what effect will these opportunities have on the industry in the next 10 years?

Ipsen has two technical training programs: Ipsen U and the Ipsen Corporate Academy.

Ipsen U is a three-day practical course to build and refresh technical aptitude for customers and employees alike. The blend of lectures and hands-on training enables metallurgists, new college graduates, operators, engineers, and others to form bonds with others in the class. It is incredible to experience how a dozen individuals can go into the class and then leave as a support network for one another. Ongoing training such as Ipsen U will also make sure everyone, from the new hire to the senior operator, are up-to-date on the newest technology and industry best practices.

The Ipsen Corporate Academy is our strategic initiative to bridge the skills gap by educating and nurturing technical resources. Currently, the curriculum is focused toward newly hired Ipsen engineers and field service technicians. Ipsen adjusts the course content based upon needs in the market at the given time.

During this five-month training program, participants learn Ipsen's core values, culture, and fundamental job skills through classroom presentations, hands-on troubleshooting experience, and on-the-job training. Since Ipsen employs the largest and most skilled aftermarket team in the business, customers benefit from this program by having better access to on-site inspections, evaluations, repairs, installation, and support for their heat-treating and auxiliary equipment.

In addition to Ipsen's educational tools, the MTI Educational Foundation also offers scholarships. How do those programs enable the other's success?

According to its website, the Metal Treating Institute Educational Foundation's mission is "building and attracting tomorrow's heat-treat talent."

With furnace building being such a niche industry, the scholarship program helps provide exposure to students who can eventually work for furnace suppliers, builders, or heat-treat customers. It is a well-established connection point for students to find their way into this profession. The ideal outcome for programs like this and Ipsen U is to work together to shorten the learning curve the workforce gap poses.

How can businesses wanting to participate in Ipsen U or the Ipsen Corporate Academy learn more about it?

Those interested in Ipsen U or the Academy should keep an eye on Ipsen's website for the announcement of 2022 dates: www.ipsenusa.com/ipsen-customer-service/training, or connect with their local regional sales engineer for more information.

MORE INFO www.ipsenusa.com

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