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PROCESS CONTROL / PYROMETRY

EFFECT OF VARIOUS HEAT-TREATMENT METHODS ON AISI 4140 STEEL

COMPANY PROFILE ///

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EFFECT OF VARIOUS HEAT-TREATMENT METHODS ON AISI 4140 STEEL

The effects of annealing, normalizing, and oil quenching on the hardness and impact energy of AISI 4140 steel over an austenitization heat-treatment temperature range of 900-950°C and holding times of 1-2 hours, are studied.

SIMULATION-BASED PREDICTION OF THE THERMAL PROCESS EMISSION MEASURED BY PYROMETRY OF 316L STAINLESS STEEL

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- » **Ipsen USA announces order from Urschel Laboratories.**
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2026-2028 PRESIDENT ///

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International Federation for Heat Treatment (IFHTSE)



The international association whose primary interest is heat treatment and surface engineering shares news of its activities to promote collaboration on issues affecting the industry.

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Industrial Heating Equipment Association (IHEA)

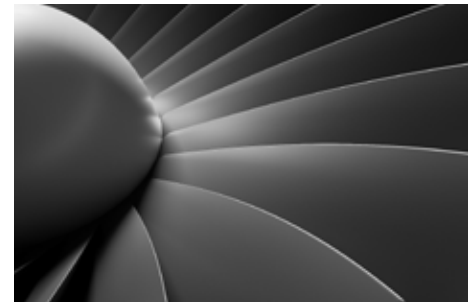


The national trade association representing the major segments of the industrial heat processing equipment industry shares news of its activities, training, and key developments in the industry.

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Pyrometry and process control take center stage

The March issue of *Thermal Processing* looks at activities vital to the heat-treat industry, namely pyrometry and process control.

Pyrometry is a subject that is a vital part of making sure equipment performs optimally, while process control is also another necessary component of heat treating in making sure equipment maintains its proper temperatures across the board. When companies decide to upgrade their existing equipment, it's important to make sure the electronics and hardware that monitor those functions are updated as well.

In our feature article, Sharan Mudda, Ananda Hegde, Sathyashankara Sharma, B. M. Gurumurthy, Manjunath Shettar, and M. C. Gowrishankar share their insights on the effect of various heat-treatment methods on AISI 4140 steel.

In this month's second feature on pyrometry, Tobias Baranzke, Sebastian Bremen, and Florian Eibl take a deep dive into the simulation-based prediction of the thermal-process emission measured by pyrometry of 316L stainless steel.

For years now, *Thermal Processing* has been proud to bring to you updates from the International Federation of Heat Treating and Surface Engineering (IFHTSE). Through contributor Scott MacKenzie, *Thermal Processing* has formed a good relationship with this important group of professionals and academics and what they do in the heat-treating and surface engineering world.

The group elects a new president every two years, and this cycle, Dr. Lesley Frame was recently elected to this important position.

In the March Q&A, I had the pleasure of talking with Dr. Frame and asked her to share her thoughts on what her plans are as IFHTSE president and what the organization can do for academics worldwide.

That's just a taste of what you'll find in this month's issue of *Thermal Processing*.

I also want to take the opportunity to say that if you're looking for a forum to share your expertise, please hit me up with suggestions at the email below so we can continue to make *Thermal Processing* the best heat-treat source it can be.

As always, thanks for reading!

KENNETH CARTER, EDITOR
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The Tenova and GE Vernova project supports Japan's Green Transformation and Nippon Steel's 2050 Carbon Neutral Vision. (Courtesy: Tenova)

Tenova teams to supply record EAF to Nippon Steel

Nippon Steel Corporation chose Tenova to supply a record-breaking Consteel® electric arc furnace for Nippon Steel's Yawata Area at Kyushu Works. Tenova teamed with GE Vernova, whose direct feed system will power the EAF.

Tenova is a leading provider of sustainable solutions for the metals and mining industries.

Once installed, the new furnace will become the world's most powerful EAF with a heat size of 340 tons. This unprecedented power level will enable the use of high percentages of virgin iron units, which are essential for producing high-quality steel grades. GE Vernova will supply its direct feed power system, providing the high-stability power needed for such an advanced and unique installation.

The Yawata project is a landmark investment that combines innovation and sustainability and represents a crucial step in Nippon Steel's pathway to carbon neutrality by 2050, shifting from blast furnace to EAF steelmaking in line with Japan's Green Transformation (GX) Promotion Act and the company's long-term decarbonization strategy.

"We are thrilled to collaborate once again with one of the world's leading steelmakers, Nippon Steel," said Paolo Argenta, Tenova executive vice president, Upstream Business Unit. "This record-setting EAF is not only an engineering achievement, but it also embodies a shared commitment with GE Vernova to sustainability that defines the future of our industry."

"We are proud to collaborate with Tenova and Nippon Steel on a project that represents the future of sustainable steel production," said Ed Torres, business leader, Power Conversion and Storage, GE Vernova. "Our direct feed solution shows how advanced power technologies can support energy-

intensive industries in operating more efficiently and reliably while accelerating their long-term decarbonization goals."

MORE INFO www.tenova.com
www.governova.com

Ipsen USA announces new order from Urschel Laboratories

Ipsen USA has received a new equipment order from Urschel Laboratories, Inc., a global manufacturer of precision food cutting equipment headquartered in Chesterton, Indiana. The order includes a MetalMaster® HR 54x48 2-bar vacuum furnace, which will replace an Ipsen furnace that has been in continuous production since 1986.

The new furnace will be used to heat treat 400-series stainless steel knife systems that are critical to Urschel's food processing machinery. The replacement of a 40-year-old Ipsen furnace highlights both the longevity of Ipsen equipment and the long-standing trust between the two companies.

This purchase marks Urschel's sixth Ipsen vacuum furnace. In addition to the new MetalMaster, Urschel currently operates two TITAN® LT6 2-bar vacuum furnaces and another MetalMaster HR 54x48 2-bar furnace purchased in 2014. Ipsen furnaces play a central role in Urschel's heat-treating operations, supporting annealing, hardening, tempering, and brazing processes required for high-performance, food-grade cutting components.

Ipsen and Urschel share a relationship spanning 40 years, built on consistent performance, reliability, and technical support. Urschel's continued investment in Ipsen technology reflects a long-term strategy focused on operational efficiency, product quality, and equipment longevity.

"This order reflects the durability of Ipsen furnaces and the long-term confidence cus-



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.



Urschel Laboratories, Inc. has purchased an Ipsen MetalMaster® HR 54x48 2-bar vacuum furnace to replace a MetalMaster furnace from 1986 that has been in continuous use. (Courtesy: Ipsen USA)

tomers place in our technology,” said Ipsen sales director Matt Clinite.

Every Urschel cutting machine manufactured worldwide is produced at the company’s Chesterton facility, where Ipsen vacuum furnaces have supported production demands for decades.

MORE INFO www.ipsenglobal.com

Automotive supplier expands with Gasbarre belt furnace

Gasbarre Thermal Processing Systems has been selected by a long-standing customer to supply a new 24-inch belt, four-zone brazing furnace supporting automotive component production.

The system will be installed at an established Midwest manufacturing facility as the customer expands capacity to meet increased production requirements.

The order represents the customer’s third Gasbarre brazing furnace, building on the success of two existing installations currently supporting day-to-day operations. The new furnace will be used for stainless steel braz-

ing of automotive parts, including braking and fluid line components, where consistent thermal processing and atmosphere control are essential to quality and reliability.

Designed for controlled-atmosphere processing, the system will operate in a nitrogen/hydrogen atmosphere and is engineered to support repeatable brazing results, stable production flow, and operator-friendly use.

The customer selected Gasbarre based on the proven design and performance of its existing furnaces. Prior installations have delivered dependable uptime with minimal issues, while maintaining a clean, accessible layout that operators find easy to use — a key factor when adding capacity in a high-output environment.

“When a customer returns for additional capacity, it’s the strongest validation of reliability and long-term value,” said Ben Gasbarre. “This order reflects the trust we work to earn through durable equipment, repeatable processing, and responsive support.”

Gasbarre Thermal Processing Systems designs and manufactures engineered thermal processing equipment for demanding industrial applications. ♪

MORE INFO www.gasbarre.com



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INTERNATIONAL FEDERATION OF HEAT TREATMENT AND SURFACE ENGINEERING

Welcome address from the new IFHTSE president



Lesley Frame is associate professor of Materials Science and Engineering, past-UTC professor of Innovation, and director of the Center for Materials Processing Data at the University of Connecticut.

Dear members and friends of IFHTSE: I am honored to step into the role of president for our federation. Our organization has a long history of connecting heat treaters and surface engineers from around the world through academic discussion, research collaborations, and industrial advancements in our field.

Under Prof. Massimo Pellizzari's leadership and with the unwavering support of our IFHTSE executive committee these past two years, we have seen improvements to IFHTSE communications (including the website, newsletter, social media presence) and several successful conferences held in the U.S., Canada, China, and Italy. I thank Prof. Pellizzari for his leadership and mentorship as I prepared for my new role with IFHTSE.

Additionally, I am very grateful for the advice, contributions, and guidance from the IFHTSE executive committee and governing council as we identify future opportunities for our organization. Most importantly, I thank two who have dedicated decades of service to IFHTSE and who have supported and encouraged me to take on this leadership role: Scott MacKenzie and Stefan Hock.

During the next two years, we will continue to expand opportunities for early career professionals at IFHTSE events, and we will promote collaboration and communication within the heat-treating field through international conferences, symposia, and congresses. We look forward to hearing from the friends and members of IFHTSE to learn how the organization can serve you better, and we are eager to expand our federation to more regions around the world. I'm excited to see many of you at our next World Congress in Cologne, Germany this coming fall and at several of our regional events scheduled for the coming year.

Warm Regards -- Lesley D. Frame

MEMBERS IN THE NEWS

Prof. Bojan Podgornik elected to Executive Committee

Prof. Bojan Podgornik was recently elected a member of the executive committee by the Governing Council. He is a researcher and head of the Metallic Materials Department at the Institute of Metals and Technology (IMT), Slovenia.

He is also actively involved in higher education as a professor in the fields of contact mechanics, tribology, heat treatment, and surface engineering. His research activities encompass heat treatment, surface engineering, tribology, additive manufacturing, and fatigue and failure analysis, with a strong emphasis on transferring fundamental research outcomes into industrial practice. He is an author of more than 200 research papers, delivered more than 60 invited lectures, contributed to eight book chapters, organized four international conferences, and holds three patents. In 2024, he was awarded the IFHTSE Fellowship.

Besides research and education, Podgornik is deeply engaged in professional societies. He serves as secretary general and treasurer of the Slovenian Society for Heat Treatment and as vice president of the Slovenian Society for Materials. He is an active member of several national and international engineering and materials-related societies, contributing to the development of strong links between the Slovenian heat-treatment and tooling industry, the national research community, and IFHTSE.

He also acts as a professional adviser within the Slovenian Strategic Research and Innovation Partnership for Materials (SRIP MATPRO), where he contributes to strengthening international collaboration, knowledge transfer and strategic links between research and industry.

Sabine Denis to receive IFHTSE Medal

Professor Sabine Denis will receive the IFHTSE Medal, as decided by the Executive Committee. The Medal will be given during the awards ceremony of the 31st IFHTSE World Congress in Cologne, Germany, October 13-15, 2026.

The citation reads: "For her lifetime achievements in numerical modeling of the interplay of temperature, phase transformations, and residual stress in heat treatment, in particular the importance of deformation and transformation plasticity."

Denis began her career at École des Mines de Nancy with a BSc in 1977 and an MSc in 1980. In 1981, she was employed by CNRS, where she defended her thesis in 1987, whereafter she became CNRS Research Director in 1995 and later University Professor in 2001 at the Faculty of Sciences of Nancy. [MS2.1] She spent her entire education and career in the same laboratory, which became the "Laboratory of Science and Engineering of Materials and Metallurgy" (LSG2M). It later merged with the University of Lorraine in 2009 to become the Institut Jean Lamour (IJL).

Denis was one of the pioneers in the modeling of the origin of residual stresses formed during heat treatments of metal alloys with phase transformations (steels, aluminum, and titanium alloys). She made major contributions in the study of the role of transformation deformation and transformation plasticity on these stresses. In addition, micromechanical approaches have made it possible to better understand the modeling of transformation plasticity such as local stress fields in the vicinity of precipitates.

Denis was earlier awarded the IFHTSE Fellowship in 2006 "in recognition of globally acknowledged leadership in the development of mathematical modeling principles and practices and their application to the benefit and advancement of heat treatment and surface engineering science and technology."

CONFERENCE UPDATES

BHTS'2026

April 16-17

Istanbul, Turkey

BHTS'2026 – the 3rd Bosphorus International Heat Treatment Symposium will be April 16-17, 2026, at the Sabancı University Performing Arts Center in Istanbul, in collaboration with the Metal

Heat Treatment Industrialists Association (MISAD) and UCTEA Chamber of Metallurgical and Materials Engineers' Training Center (METEM). The chairman of the event is Nuri Kiziltan.

The symposium will provide a comprehensive platform to discuss heat treatment, one of the strategic fields of manufacturing, considering the latest technological and scientific developments. The goal is to bring together all stakeholders, including industry leaders, engineers, researchers, academics, and end users, to exchange knowledge, build collaborations, and shape the future of the field.

» **For more info:** info@bhtsheat.com or www.bhtsheat.com/en

7th Asian Conference on Heat Treatment and Surface Engineering

September 18-21, 2026

Chengdu, China

The 7th Asian Conference on Heat Treatment and Surface Engineering is a quality event, with typical attendance at more than 1,000 attendees. The location is very walkable, beautiful, and unique. Chengdu is the capital city of Sichuan and is noted for its spicy food and hot pots.

31st IFHTSE World Congress

October 13-15, 2026

Cologne, Germany

Organized by AWT – Arbeitsgemeinschaft Wärmebehandlung + Werkstofftechnik e. V., the 31st IFHTSE World Congress will be October 13-15, 2026, in Cologne, Germany, at the International Conference and trade fair. It will include three events: HK 2026, ECHT 2026, and the 31st IHTSE World Congress

This will truly be a huge event. If you have never attended the AWT HK (Härtereikongress) event, this is one of the largest (if not the largest) heat treating trade show in the world. This, combined with ECHT 2026 and the 31st World Congress, will be the ONE event to attend.

This large conference is organized in cooperation with the International Federation for Heat Treatment and Surface Engineering (IFHTSE) as well as the European heat treatment associations from France, Austria, Switzerland, the Czech Republic, Slovakia, and the Benelux countries. Due to the expected number of lecture registrations, the congress event is planned as a three-day event. The language of the conference will be English.

» **More info:** www.hk-awt.de



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Stronger together: Engage, lead, and shape the future with IHEA



The thermal process heating industry is evolving at an unprecedented pace. From sustainability initiatives and energy management efforts to economic pressures and tariff concerns, the challenges and opportunities facing our marketplace demand collaboration, innovation, and leadership. That's where IHEA members make the difference.

IHEA is more than an association, it's a working community of professionals committed to advancing the thermal processing industry. Membership means having a voice in conversations shaping our future and playing an active role in developing solutions that move the industry forward.

ENGAGE. CONTRIBUTE. LEAD.

IHEA members are driving change. Through active committee participation, members collaborate on initiatives that address sustainability challenges, provide clarity on decarbonization strategies and promote balanced, fact-based industry education. Together, members share technical expertise and ensure our industry is represented with accuracy and integrity.

Members also gain exclusive access to tools that support smarter business decisions, including IHEA's monthly Executive Economic Update Report, keeping you informed on the trends and forces impacting your company and customers.

EDUCATION THAT ELEVATES THE INDUSTRY

Membership strengthens IHEA's ability to deliver high-quality education and training programs designed to support both suppliers and end users. Members receive discounted access to events, seminars, and online courses, making it easier to stay competitive in a fast-changing environment.

Just as important, membership supports the continued development of new educational resources and expanded programming planned throughout 2026, ensuring our industry remains informed, skilled and future-ready.

CONNECTIONS THAT MATTER

In an industry built on relationships, networking remains invaluable. IHEA events provide opportunities to build meaningful connections with peers, industry leaders,

and emerging professionals. These conversations spark ideas, partnerships, and solutions that benefit the entire thermal processing community.

BE PART OF THE PROGRESS

Engage with peers. Contribute your expertise. Strengthen the industry. Learn more about membership benefits and what's ahead for 2026 at www.ihea.org.

ENGAGING THE INDUSTRY: HIGHLIGHTS FROM IHEA'S 2026 ANNUAL MEETING

Member engagement is the core focus for this year, and IHEA's 2026 Annual Meeting brought that commitment to life through active participation and meaningful dialogue. The meeting delivered valuable insights, lively discussion, and plenty of opportunities for members to connect and engage. From economic forecasts and energy management strategies to global trade realities, the program sparked thoughtful conversations about the challenges and opportunities ahead for the industry. Attendees gained practical takeaways from timely presentations while also participating in interactive roundtable discussions that gave everyone a voice.

Of course, it wasn't all business. The beach team-building event brought out creativity and camaraderie in full force during the sand-



cance of Spore's appointment and the value he brings to the association's leadership.

"Chad Spore's election as IHEA Treasurer marks a historic milestone for our association," she said. "As the first end-user officer in IHEA's nearly 100-year history, Chad brings a critical real-world perspective that strengthens our leadership and reinforces IHEA's commitment to serving the evolving needs of industry."

IHEA also welcomes Michael Stowe, Stowe & Sons PLLC, back to its Board of Directors. Stowe recently launched his own energy consulting firm, where he focuses on strategic energy management (SEM) implementation for commercial and industrial facilities, as well as the development and execution of utility-based SEM programs. He previously served on the IHEA Board while with a different organization and brought a wealth of knowledge on energy management and efficiency. IHEA is grateful to have him back in a leadership capacity.

Finalizing the lineup of IHEA's Board of Directors for 2026-2027, the following members continue their tenure: Scott Bishop, Electric Power Research Institute; Ben Gasbarre, Gasbarre Thermal Processing Systems; Brian Kelly, Honeywell Thermal Solutions; John Podach, Fostoria Infrared; Jeff Rafter, Selas Heat Technology; John Stanley, DUNGS Combustion Controls; Helen Tuttle, WS Thermal Process Technology Inc.; and Jeff Valuck, Surface Combustion, Inc.

Representing the strength and diversity of our membership, the IHEA Board of Directors is dedicated to fostering collaboration, innovation, and meaningful engagement across the industry. IHEA invites you to engage, contribute and help shape the year ahead.

castle building contest. The winning team impressed everyone by constructing a detailed sand furnace, proving once again that industrial heating professionals can bring their expertise anywhere.

From the meeting room to the beach, the event was a great reminder that the real strength of IHEA lies in the relationships, collaboration, and engagement of its members.

LEADERSHIP COMMITTED TO ADVANCING OUR INDUSTRY

As we continue building a stronger, more connected industry, the leadership of IHEA's Board of Directors plays a vital role in guiding our shared vision and advancing the priorities that matter most to our members. IHEA recently announced its 2026-27 Board of Directors and Executive Officers. Taking over as president is Jason Safarz of DUNGS Combustion Controls; vice-president is Bob Fincken of Super Systems, Inc.; and treasurer is Chad Spore of John Deere. Gary Berwick of Dry Coolers, Inc. assumes the past president position.

IHEA Executive Vice President Anne Goyer emphasized the signifi-

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Modeling the thermal effect of transferring parts from furnace to quench

Capturing the critical transfer step

One of the most overlooked processes in heat treatment of steel parts is the transfer step where parts are moved from the heating furnace to the quenching system. During an air-transfer step, the surface of a hot steel part quickly loses heat to the environment through radiation and convective forces. Arguably, the austenitizing and quenching steps have more going on metallurgically, but the transfer step sets up a thermal gradient in the part that goes into the quench step. From a modeling perspective, including the transfer step in the analysis is paramount to capturing the phase transformation timing during the quench step, which can have a significant effect on the distortion and residual stress prediction. Furthermore, the geometry of the part, or the chemistry of the steel, can increase the sensitivity the transfer step has on the final product. For an accurate heat-treatment simulation, the transfer step must be included in the analysis to capture the heat loss and provide more accurate results for distortion and residual stress.

Furnace operators often use infrared pyrometers during the transfer step to measure the temperature of the part going into the quench step. Experienced operators can estimate the temperature of the part surface by looking at the color of the part during the transfer, but these methods only provide a superficial measurement and cannot look into the part to see the steep thermal gradient from the surface. Simulation can provide more information about the overall temperature gradient in the part going into quench, including for different transfer times, capturing the effect of process consistency. This allows heat treaters to explore the interaction between material hardenability and processing conditions, helping to improve their understanding of their specific process. Low alloy parts, with thin cross sections, become especially sensitive to the timing of the transfer step. Due to their low hardenability these parts may start transforming from austenite to diffusive phases before getting to the quench, reducing their mechanical performance. Figure 1 shows an example part consisting of a one-inch cross section for the body and a quarter-inch cross section for the webbing. The figure also includes a temperature contour showing how the different sections would cool differently during air transfer.

The hardness results for the one-inch cylinder models with transfer times starting at zero seconds (no transfer step) up to 90 seconds are shown in Figure 2. The results show the surface hardness of an integrated transfer of zero seconds of transfer time to be about 42.3

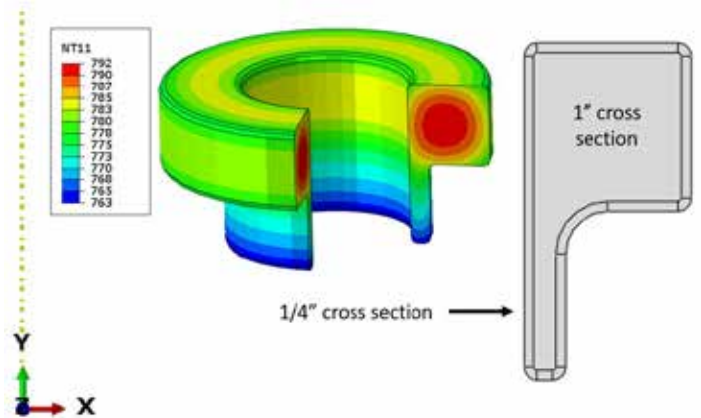


Figure 1: A simplified gear geometry showing an example of a thin and thick sectioned part.

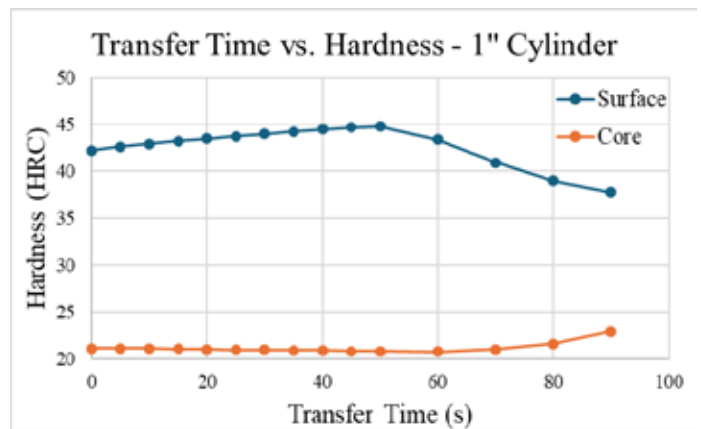


Figure 2: Simulated transfer time vs. hardness for the surface and core of a one-inch cylinder.

HRC, and the core hardness of 21.2 HRC. As transfer time increases, the surface hardness of the cylinder also increases, non-intuitively, until about 50 seconds of transfer time when the surface hardness reaches its peak of nearly 45 HRC (44.8 HRC). During the same time frame, the core hardness decreases slightly from 21.2 HRC with no transfer time to 20.8 HRC at 50 seconds of transfer time. After 50 seconds of transfer time, the surface begins to see a reduction of hardness from some diffusive transformation at the surface during the transfer reaching a minimum of 37.7 HRC after 90 seconds of transfer

SENSITIVITY ANALYSIS WITH HTP SIM

A case study was developed to look at the sensitivity to the duration of the transfer step on the final surface and core hardness in AISI 1020 alloy. A one-inch cylinder cross section and a quarter-inch cylinder cross section were used to represent different section thicknesses. The heat-treatment process was modeled in the HTP Sim utility from DANTE and the process steps are as follows:

- » Furnace heating (2 hours – 800°C ambient).
- » Air transfer (0-90 seconds - 400°C film temperature).
- » Water quench (1/2 hour – 20°C water temperature).
- » Air-cool to room temperature (1 hour at 20°C).

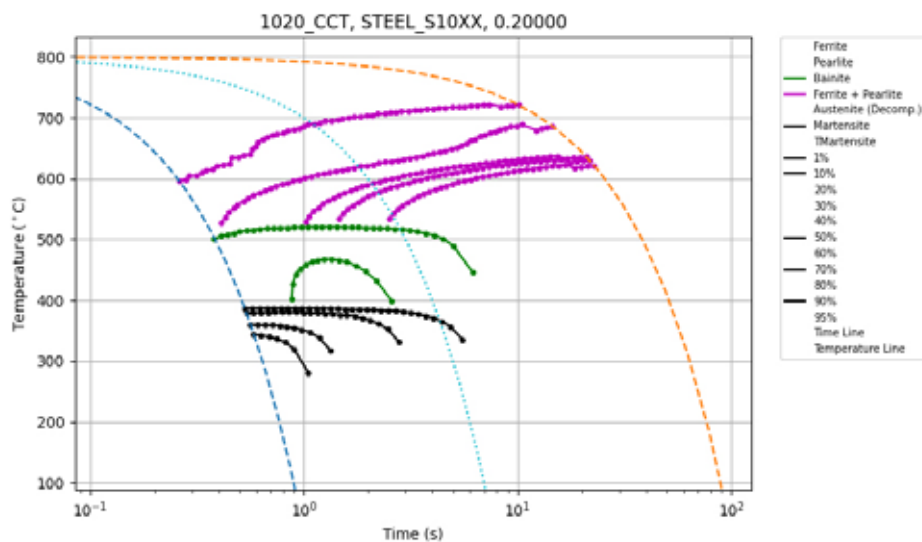


Figure 3: CCT diagram of AISI 1020 steel generated from the DANTE material database.

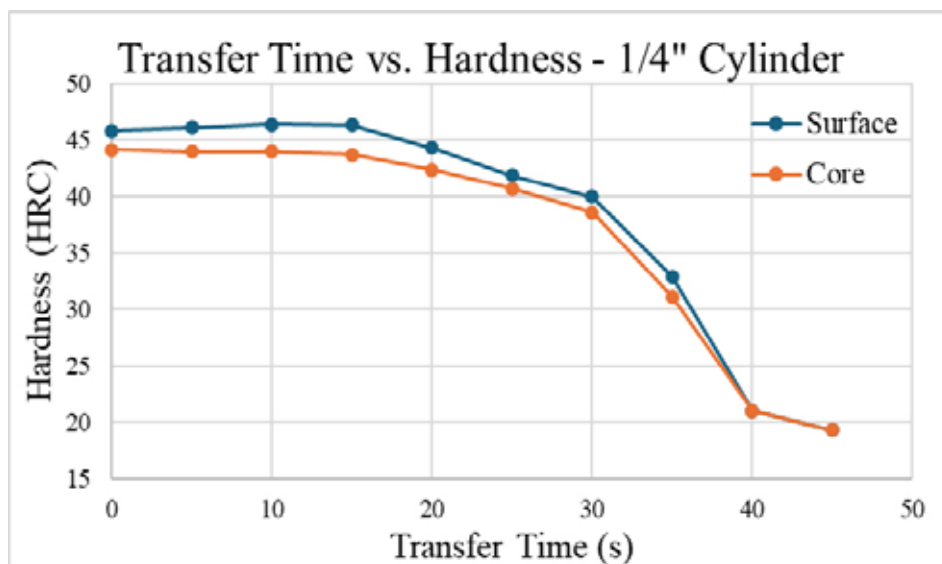


Figure 4: Simulated transfer time vs. hardness for the surface and core of a 1/4" cylinder.

time. Conversely, the core shows some hardening as transfer time increases past 50 seconds, reaching a maximum of about 23 HRC with a transfer time of 90 seconds.

The reason for the increase in surface hardness up until 50 seconds can be explained by the heat loss at the surface of the part. As the surface cools during transfer, the very near surface is closer to the martensite start temperature allowing the surface to cool fast enough to form more martensite. After 50 seconds, the surface clips the “nose” of the ferrite transformation as it cools, forming some soft ferrite before the martensite transformation can begin. Longer transfer times produce more ferrite, reducing the surface hardness. For the core of the cylinder, the hardness remains relatively constant until the transfer time is sufficient to remove enough heat that the core can transform to phases other than ferrite and pearlite, such as bainite or even martensite, increasing the core hardness at the expense of surface hardness. Figure 3 shows a continuous cooling transformation (CCT) diagram of 1020 steel generated from the DANTE material database illustrating the phases that can be developed during different rates of cooling.

For the quarter-inch cylinder, shown in Figure 4, the surface and

core hardness is relatively close, 46 HRC at the surface and 44 HRC in the core, with no transfer time. Due to the reduced section thickness, the cylinder cools more uniformly than the one-inch cylinder, reducing the hardness difference from surface to core.

Again, the model shows a surface-hardening effect with increased transfer time up to 15 seconds, after which both the surface and the core hardness quickly drop with increased transfer time. After about 40 seconds of transfer time, the surface and core hardness are equal at about 21 HRC.

Compared to the one-inch cylinder, the thin cylinder section is much more sensitive to transfer time. The one-inch cylinder model showed an increase in surface hardness up to 50 seconds, while the thin section cylinder hardness was already severely reduced after 20 seconds of transfer time. With parts that include thin and thick sections, the transfer time consistency becomes an increasing concern to balance these regions.

CONCLUSION

This work demonstrates that the often-overlooked air-transfer step between furnace heating and quenching plays a critical role in determining final hardness and phase composition in heat-treated steel components. Through simulation, a sensitivity study on AISI 1020 cylinders of varying section thickness revealed that transfer time fundamentally alters thermal gradients entering the quench, shifting phase transformation behavior at both the surface and core.

Thick sections exhibited a non-intuitive increase in surface hardness with moderate transfer times before declining due to diffusive transformations. Meanwhile, thin sections proved highly sensitive, with hardness rapidly deteriorating after short delays.

These results highlight that part geometry and hardenability amplify the metallurgical consequences of transfer conditions. For an accurate heat-treatment simulation, the transfer step must be included in the analysis to capture the heat loss and provide more accurate results for distortion and residual stress. By incorporating this step, simulations more closely represent real-world processing conditions, enabling engineers to better predict material response, optimize cycle parameters, and ensure consistent mechanical performance across complex geometries. The transfer step may be brief in time, but the thermal gradient it sets up prior to quenching may have a significant impact on the final hardness and overall heat treat response of a part. ☞

ABOUT THE AUTHOR

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Solution treatment, quenching, and aging are involved to optimize high-temperature strength, creep resistance, and ductility.

Heat treatment of nickel-based superalloys

Heat treatment of nickel-based superalloys is designed to control precipitation, dissolution, and coarsening of strengthening phases, primarily the ordered γ' phase in an FCC γ matrix, along with carbides and other intermetallics. These treatments tailor microstructure for creep resistance, fatigue strength, and environmental stability in extreme turbines and aerospace environments.

Nickel-based superalloys are complex, multi-component FCC alloys built on a face-centered-cubic γ Ni-rich matrix with coherent ordered L_{12} γ' precipitates, typically $Ni_3(Al, Ti)$. The presence of the γ' precipitates provide the high temperature strength by impeding dislocation motion. There are two different classes of nickel-based super alloys. Polycrystalline and directionally solidified (DS) alloys rely significantly on grain-boundary strengthening and carbide distributions, whereas single crystal (SX) alloys eliminate grain boundaries and depend more heavily on optimized γ/γ' morphology and rafting behavior under service conditions [1] [2].

Typical heat-treating cycles for nickel-based super alloys involve solution heat treatment, quenching, and multiple aging steps. The solution heat treatment consists of heating to approximately 980-1,200°C (depending on alloy) to just below the incipient melting point to dissolve non-equilibrium γ' , carbides, and segregated phases, followed by quenching or rapid cooling to retain a supersaturated γ matrix [2] [3]. After quenching, or controlled cooling, aging is accomplished in either a single or multi-step process. The alloy is heated to a lower temperature than the solution heat-treatment temperature to nucleate and grow a controlled population of γ' and secondary carbides [2] [3].

There are two different methods for the solution heat treatment of nickel-based superalloys. The first method is a full solution heat treatment, where the temperature is raised to above the γ' solvus for a sufficient time to dissolve nearly all primary γ' and eutectic constituents. This maximizes homogenization but risks incipient melting in segregated regions [2] [4]. Partial solution heat treatment involves heating to slightly below the γ' solvus. This leaves a small fraction of residual primary γ' but eliminates the risk of incipient melting. By selecting the proper time and temperature, segregation gradients can be reduced, and incipient melting is avoided. Proper control of grain size is also achieved.

After solution treatment and quenching, the supersaturated γ matrix is metastable and will precipitate γ' on aging. The aging parameters of time, temperature, and cooling rate control the γ' morphology (spherical, cuboidal, plate-like), and the γ' volume fraction and size distribution. Typically, two-stage aging is used [1] [4]. In the first stage

aging (about 1,080-1,150°C, depending on alloy) the primary γ' nucleates heterogeneously and grows into cuboidal precipitates, establishing a coarse, coherent matrix. A lower temperature (850-900°C) age step follows where secondary and tertiary γ' form within the remaining supersaturated matrix, producing a refined γ' distribution that enhances yield strength and low-cycle fatigue resistance [1] [5] [6].

The nucleation and growth of γ' are governed by classical precipitation kinetics in a supersaturated γ matrix. Nucleation rates are maximized at intermediate aging temperatures and growth driven by solute diffusion. This is like the aging of precipitation hardening



Nickel-based superalloys, often used in jet engines, are the largest class of superalloys due to excellent high-temperature strength and oxidation resistance. (Courtesy: Shutterstock)

of aluminum alloys [7]. Coarsening follows Ostwald ripening, with a cube-root time dependence of precipitate radius under diffusion-controlled conditions, though elastic interactions and coherency strains modify coarsening behavior in high-volume-fraction γ' systems [1].

In general, the goal is to have a γ' volume fraction of approximately 60-70 percent, depending on the application. The primary cuboidal γ' precipitate size is typically on the order of 100–500 nm, and for secondary/tertiary γ' , the spacing is 40-60 nm. The cuboidal precipitates minimize coherency strain in the matrix [1] [5] [3]. Over-aging at either primary or secondary aging temperatures leads to coarsening of γ' and reduced precipitation

strengthening. At the same time, the matrix may contain a greater fraction of very fine γ' that can coarsen rapidly under service, causing unstable mechanical response [3].

Additively manufactured nickel-based superalloy parts produced with laser or electron beam powder-bed fusion start with very fine microstructures, high dislocation densities, and high residual stresses. Multiple stress-relief operations are often needed, followed by hot isostatic pressing (HIP) to remove porosity. The part is then processed normally using conventional solution-aging sequences to develop a γ/γ' microstructure comparable to cast or wrought material [3].

CONCLUSION

In this article, I reviewed the basic steps necessary to heat treat nickel-based superalloys. The solution heat treatment brings everything into solution, but care must be taken to avoid the onset of incipient melting. This is followed by quenching or controlled cooling to produce a supersaturated γ matrix. Two-step aging is used to control the size and morphology and distribution of γ' in the matrix.


Should you have any comments or question regarding this article, or have suggestions for further articles, please contact the editor or myself. ✉

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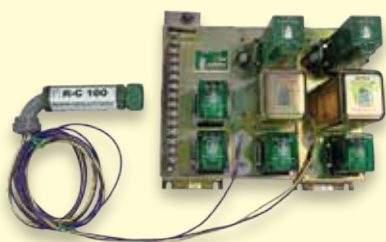
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PROCESS CONTROL / PYROMETRY

EFFECT OF VARIOUS HEAT-TREATMENT
METHODS ON
AISI 4140 STEEL

The effects of annealing, normalizing, and oil quenching on the hardness and impact energy of AISI 4140 steel over an austenitization heat-treatment temperature range of 900-950°C and holding times of 1-2 hours, are studied.

By SHARAN MUDDA, ANANDA HEGDE, SATHYASHANKARA SHARMA, B.M. GURUMURTHY, MANJUNATH SHETTAR, and M.C. GOWRISHANKAR

AISI 4140 steel is one of the important categories in the steels with a wide range of applications including but not limited to automotive, general machinery, and the oil and gas industry. In the current study, an effort is made to understand the effects of heat-treatment parameters, such as heat-treatment temperature and holding time, on the mechanical properties of AISI 4140 steel, and to optimize these parameters to obtain the superior combination of mechanical properties. The three important heat treatments used in this study are annealing, normalizing, and oil quenching. The heat-treatment parameters such as temperature and time are varied at three different levels of 900, 925, and 950°C, and 1, 1.5, and 2 hours respectively. Using the full factorial method, nine experiments were carried out with all the possible combinations of temperature and time as the variants. In each of the tests, hardness and impact energy values were evaluated using appropriate tests, while microstructural changes were analyzed through a scanning electron microscope (SEM). The results obtained through statistical analysis have shown that combination of 900°C with 2 hours for annealing, 919°C with 2 hours for normalizing and 944°C with 1 hour for oil quenching as the optimum combination of heat-treatment parameters for superior combination of hardness and impact energy. Results showed increasing temperature led to grain coarsening, reducing hardness but improving impact energy. Regression equations generated in this study that have R square value more than 90% may be used to predict the hardness and impact energy for any value of temperature and time which is within the range of values considered for this study.

INTRODUCTION

AISI 4140 is commonly used in the manufacturing of structural components that demand high strength, toughness, and wear resistance. This steel is widely used in automotive, aerospace, defense, and industrial machinery, where mechanical reliability under dynamic loading conditions is needed. Its mechanical properties can be significantly enhanced with appropriate heat-treatment processes, which alter the microstructure and change the mechanical properties such as hardness and impact energy. AISI 4140 is an alloy steel containing 1.36% Cr and 0.215% Mo, known for its good strength and fatigue resistance. Heat treatment plays a critical role in controlling the final properties of steels. Processes such as annealing, normalizing, and oil quenching are commonly used to achieve desired combinations of hardness and toughness. It may be noted that EN19 and 42CrMo4 steels, which are similar in mechanical performance but differ in chemical composition and standards, have been considered as equivalent steels to AISI 4140, only in application context and not in strict metallurgical terms, for the sake of literature review.

A lot of research has been carried out to study the effects of various heat-treatment processes on mechanical properties of AISI 4140 steel. Kandpal et al. [1] found hardening produces a martensitic structure, increasing hardness, annealing produces a ferritic structure with higher impact energy but lower hardness, while normalizing results in a ferrite pearlite mix that has a balance in toughness and hardness.

To study the effects of quenching on AISI 4140 steel, Basori et al. [2] quenched the steel at varying holding times, in the same media at a fixed cooling rate, and found that, as the holding time increased, there was a reduction in retained austenite and refinement in the martensite structure that led to an increase in hardness from 215 VHN to 545 VHN. To study the effects of various heat treatments on AISI 4140 steel, Bhagyalaxmi et al. [3] carried out annealing, hardening, and tempering heat treatments and found hardening gave highest hardness, tempering improved tensile strength, and annealing had the highest ductility. Mahmood et al. [4] found slower air-cooling rates enhance strength and tolerance, while faster cooling rates increase hardness. When austempering heat treatment was carried out at higher temperatures for AISI 4140 and 4340 steels, by Bilal et al. [5], at higher austempering temperatures, due to the formation of a coarse bainite martensite structure, there was an increase in hardness and impact energy for both the steels, while lower temperatures resulted in fine bainite martensite structures which offered better balance in strength and toughness. Similarly, when Badaruddin et al. [6] carried out austempering heat treatment on AISI 4140 steel, it was found austempering at 362°C formed a bainite-martensite-retained austenite structure with high-tensile strength and strong fatigue growth resistance, and multi-austempering further improves toughness due to formation of thicker retained austenite and bainitic structure. It has also been found double quenching and tempering improved the impact energy of the steel without significantly affecting hardness or strength [7]. Laxmi et al. [8] and Passanha et al. [9], showed increasing tempering time, temperature, or modifying quenchant oil viscosity improved impact energy but reduced hardness with optimal results obtained at mid-range tempering values and moderate oil viscosity. It has generally been observed that quenching and tempering leads to development of tempered martensite, which improves the hardness, tensile strength, and corrosion resistance of the steel [10]. However, longer holding times during heat treatment tend to reduce the hardness and corrosion resistance of the steel due to carbide precipitation and resulting microstructural changes [11]. Chuaiphan et al. [12], who experimented on usage of AISI 4140 as base material for cane harvester cutter by enhancing its properties through heat treatment, found water quenching followed by tempering resulted in a bainite martensite structure with improved hardness and a balanced impact toughness. Zhang et al. [13] carried out quenching of AISI 4140 steel and found one of the reasons quenching leads to low impact tough-

ness is because of high hydrogen absorption after austenitization, which results in quench cracks. The effects of quenching in various media on the properties of AISI 4140 was studied by Bhagyalaxmi et al. [14], and it was found that, while water quenching gave the highest hardness, castor oil gave the best overall performance with a balance in hardness, tensile strength, and ductility.

Badaruddin et al. [15] carried out annealing and quenching heat treatments on AISI 4140 steel, and found annealed samples exhibited lower strength but greater ductility and lower cycle fatigue (LCF) life compared to the quenched tempered samples due to the ferrite pearlite structure that resists cyclic crack growth better than martensite, thus making annealing more suitable for when the steel has to be used for LCF critical applications. Sharma et al. [16] found that, when AISI 4140 steel was subjected to dual phase and austempering heat treatments, austempering, due to formation of ferrite and cementite structure, gave the highest strength and impact energy, while dual phase heat treatment resulted in ferrite martensite structure, which improved strength but lowered ductility. Jami et al. [17] reported a 35% increase in hardness after oil quenching and tempering (300-400°C), with highest hardness and torsional strength observed at 300°C. Saeidi and Ekrami [18] found a bainite-ferrite microstructure offered higher impact energy and ductility than martensite-based structures at similar hardness.

Other than conventional heat treatments, research has also been done on the effect of non-conventional heat treatments on mechanical properties of AISI 4140 steel. Senthilkumar et al. [19] found that deep cryogenic treatment at minus 196°C for 24 hours improved wear resistance of the steel by 215% over conventional heat treatment, due to austenite-to-martensite formation.

Based on the literature review, we concluded that a substantial amount of work has been carried out to study the effects of various heat treatments on mechanical properties of AISI 4140 structural steel, but very little work has been done with regards to optimization of the heat-treatment parameters to get the best combination of hardness and impact energy for the steel. This study aims to perform a comparative analysis of the heat-treatment behavior of AISI 4140 steel. The objective is to evaluate the influence of annealing, normalizing, and oil quenching on the microstructure, hardness, and impact energy of the steel. Additionally, optimization techniques are applied to determine the best set of heat-treatment parameters that maximize mechanical performance. The findings are expected to support better material selection and processing decisions in industrial applications where a balance between strength and toughness is crucial.

MATERIALS AND METHODOLOGY

Material procurement and specimen Preparation

AISI 4140 steel rods of 16 mm diameter were procured and machined to the required test specimen dimensions as per ASTM standards (as shown in Figures 1 and 2) for both Vickers microhardness, SEM analysis, and a Charpy impact test. The specimens were prepared using lathe, CNC milling, wire EDM, and slot milling machines.

Spectroscopy analysis

Spectroscopy analysis, as shown in Table 1, was carried out to make sure the material

composition of the procured AISI 4140 steel was as per AISI standards.

Heat treatment

Separate specimens were prepared for annealing, normalizing, and oil quenching heat treatments. The specimens are heated in a muffle furnace for austenitization heat-treatment temperatures and soaking time conditions as mentioned in Table 2. The heat treatment tem-



Figure 1: Microhardness and SEM analysis specimen as per ASTM E384 standards [20].

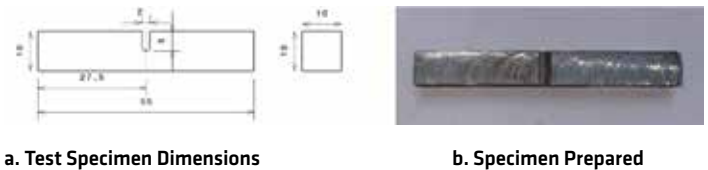


Figure 2: Charpy impact test specimen prepared as per ASTM E23 standards [21].

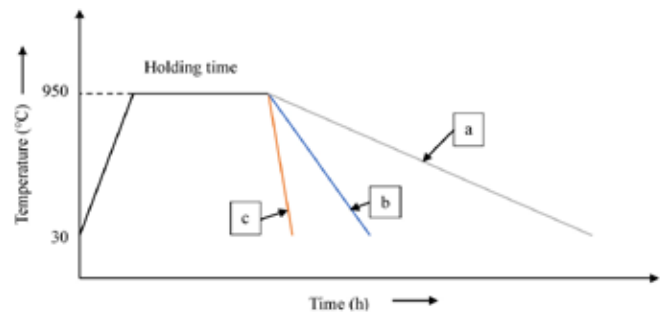


Figure 3: Heat treatment cycle (a) Annealing, (b) Normalizing and (c) Oil quenching.

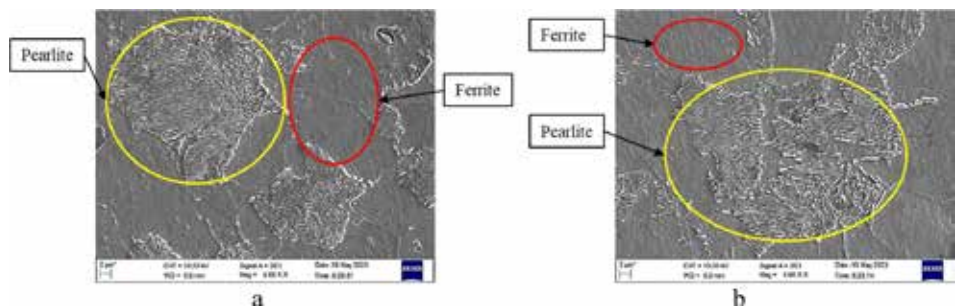


Figure 4: SEM image of AISI 4140 steel annealed at (a) 900°C for 2 hours and (b) 950°C for 2 hours.

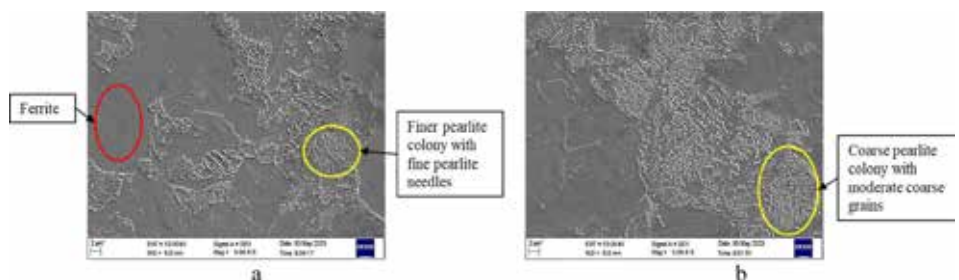


Figure 5: SEM image of AISI 4140 steel normalized at (a) 900°C for 2 hours and (b) 950°C for 2 hours.

| Element | C | Si | Mn | P | S | Cr | Ni | Mo | Fe |
|------------------------------------|-----------|-----------|-----------|--------|--------|-----------|-------|-----------|--------------|
| wt% obtained | 0.417 | 0.243 | 0.66 | <0.001 | 0.012 | 1.36 | 0.096 | 0.215 | 96.8 |
| wt% as per standards ²² | 0.35-0.45 | 0.15-0.30 | 0.50-0.80 | <0.035 | <0.040 | 0.90-1.50 | - | 0.20-0.40 | 96.785-97.77 |

Table 1: Spectroscopy analysis of AISI 4140 steel.

| Temperature (°C) | Time (h) | Annealing | | Normalizing | | Oil quenching | |
|------------------|----------|---------------|-------------------|---------------|-------------------|---------------|-------------------|
| | | Hardness (HV) | Impact energy (J) | Hardness (HV) | Impact energy (J) | Hardness (HV) | Impact energy (J) |
| 900 | 1 | 210 | 30 | 290 | 40 | 485 | 22 |
| 900 | 1.5 | 205 | 36 | 287 | 45 | 480 | 23 |
| 900 | 2 | 203 | 43 | 284 | 48 | 478 | 24 |
| 925 | 1 | 200 | 38 | 280 | 45 | 450 | 26 |
| 925 | 1.5 | 195 | 42 | 275 | 48 | 420 | 28 |
| 925 | 2 | 190 | 47 | 270 | 50 | 400 | 30 |
| 950 | 1 | 190 | 44 | 250 | 50 | 360 | 36 |
| 950 | 1.5 | 185 | 49 | 230 | 55 | 320 | 38 |
| 950 | 2 | 183 | 54 | 219 | 60 | 286 | 42 |

Table 3: Hardness and impact test results for AISI 4140.

| Heat treatment | Factors | Adj. SS | Adj. Ms | F-Value | P-Value | % Contribution | R-sq % |
|----------------|-------------|---------|---------|---------|---------|----------------|--------|
| Annealing | Temperature | 602.000 | 301.000 | 301.00 | <0.0001 | 85.51 | 99.43 |
| | Time | 98.000 | 49.000 | 49.00 | 0.002 | 13.92 | |
| Normalizing | Temperature | 4824.0 | 2412.00 | 50.96 | 0.001 | 89.56 | 96.48 |
| | Time | 372.7 | 186.33 | 3.94 | 0.113 | 6.92 | |
| Oil quenching | Temperature | 38875 | 19437.4 | 67.23 | 0.001 | 90.59 | 97.31 |
| | Time | 2880 | 1440.1 | 4.98 | 0.082 | 6.71 | |

Table 4: ANOVA results of impact energy for AISI 4140.

| Heat treatment | Factors | Adj. SS | Adj. Ms | F-Value | P-Value | % Contribution | R-sq % |
|----------------|-------------|---------|---------|---------|---------|----------------|--------|
| Annealing | Temperature | 240.889 | 120.444 | 108.40 | <0.0001 | 57.87 | 98.93 |
| | Time | 170.889 | 85.444 | 76.90 | 0.001 | 41.06 | |
| Normalizing | Temperature | 178.667 | 89.333 | 53.60 | 0.001 | 65.23 | 97.57 |
| | Time | 88.667 | 44.333 | 26.60 | 0.005 | 32.36 | |
| Oil quenching | Temperature | 384.222 | 192.111 | 172.90 | 0.000 | 93.05 | 98.92 |
| | Time | 24.222 | 12.111 | 10.90 | 0.024 | 5.87 | |

Table 5: ANOVA results of impact energy for AISI 4140.

perature and holding time values as shown in Table 2 were chosen based on literature review [4] and preliminary trials, wherein full austenitization and homogeneity was obtained.

Full factorial method was adopted to carry out the heat treatments by covering all the possible nine combination of temperatures and time values. After heating, the annealing specimens were furnace cooled, normalizing specimens were air cooled, and oil quenching specimens were quenched in SAE 40 engine oil. SAE 40 is a single-grade oil with high viscosity at elevated temperatures, kinematic viscosity of 14 to 16 mm²/s at 100°C, making it suitable for moderate quenching applications. It provides a slower cooling rate compared to water but faster than polymer-based or air cooling, helping to reduce distortion and cracking in medium-carbon steels. The cooling rate of three heat-treatment processes is represented graphically in temperature vs. time graph in the Figure 3.

Mechanical characterization tests

ASTM E384-2220 was used as the standard for carrying out Vickers microhardness tests for assessing the hardness of all the test samples.

Charpy impact testing was carried out at the Advanced Composite Lab, Department of Aeronautical and Automobile Engineering, MIT,

| Temperature (°C) | 900 | | 925 | | 950 | |
|------------------|-----|-----|-----|---|-----|---|
| Time (h) | 1 | 1.5 | 2 | 1 | 1.5 | 2 |

Table 2: Heat treatment parameters.

Manipal. Specimens were mounted in the testing machine, and a 300 J pendulum strike was applied. The energy absorbed during fracture was recorded to evaluate impact resistance. Testing followed ASTM E23 [21] guidelines. For microstructural analysis, EVO MA18 SEM with Oxford EDS X-act, available at the Central Research Facility, MIT Manipal, was used.

RESULT AND DISCUSSION

Mechanical characterization results

The effect of heat treatment (annealing, normalizing, and oil quenching) on the mechanical properties (hardness and impact energy) of the heat-treated samples for AISI 4140 are shown in Table 3. The results, based on the average of five trials, had a standard variation of less than 3%. The respective microstructure results for each heat treatment are as shown in Figures 4, 5, and 6.

Based on data from Table 3 and analyzing the microstructure shown in Figure 4, it may be seen that hardness of AISI 4140 steel decreases, and impact energy increases with increase in annealing temperature and time. At 900°C (1-2 hours), hardness drops from 210 HV to 203 HV; impact energy rises from 30 J to 43 J due to reduced dislocations and wider pearlite spacing. At 925°C, hardness falls to 190 HV and impact energy reaches 47 J, with finer pearlite in ferrite matrix. At 950°C, steel softens rapidly (183 HV, 54 J), showing coarse pearlite and large ferrite grains. Increased interlamellar spacing drives softening and toughness.

Normalizing for AISI 4140, as observed in Table 3; Figure 5, at increasing temperatures and times, lowers hardness and boosts impact energy. At 900°C (1-2 hours), hardness drops from 290 HV to 284 HV; impact energy rises from 40 J to 48 J due to fine pearlite-ferrite structure. At 925°C, hardness declines to 270 HV and impact energy reaches 50 J as microstructure becomes more uniform. At 950°C, grain growth and coarse pearlite reduce hardness to 219 HV while impact energy peaks at 60 J. Higher temperature and time soften the steel while increasing toughness.

When AISI 4140 was subject to oil quenching heat treatment, as seen in Table 3; Figure 6, it was observed that at 900°C (1-2 hours) martensitic structure was formed, giving high hardness (485 HV to 478 HV) and low toughness (22 J to 24 J). Longer soaking increases austenite grain size, producing coarser martensite and slightly reducing hardness while improving impact energy. Similar trends occur at 925°C and 950°C. Overall, higher temperature and time reduce hardness and increase toughness due to martensite coarsening.

ANOVA

To assess the influence of heat-treatment parameters, such as tem-

perature and time, on the mechanical properties of AISI 4140 steel, a two-way ANOVA was conducted at a 95% confidence level, using MINTAB 17 statistical analysis software.

Analysis of Variance (ANOVA) is a technique that evaluates statistical significance of factors and their interactions on measured responses by partitioning total variability into contributions from each source. This helps in identifying which parameters significantly influence the outcomes. The mechanical properties evaluated were Vickers microhardness and the Charpy impact energy. The percentage contributions of each factor were also calculated to understand their relative influence on the properties.

The results of ANOVA of hardness and impact energy for AISI 4140 are as shown in Tables 4 and 5 respectively.

The ANOVA results, as tabulated in Table 4 and 5, show that, for both hardness and impact energy, heat-treatment temperature is the greater influential factor.

Temperature has nearly 85.5 % influence on the hardness of annealed specimens, 89.5 % on normalized, and 90.5 % on oil quenched specimens. For impact energy, temperature has nearly 57.87 % influence on annealed specimens, 65.2 % on normalized, and 93 % on oil quenched specimens. Even though the holding time also has some influence on hardness and impact energy, its influence is less compared to heat treatment temperature.

The main effect plots of hardness and impact energy w.r.t temperature and time, for annealing (Figure 7), normalizing (Figure 8), and oil quenching (Figure 9) of AISI 4140, depict a downward slope for hardness and an upward slope for impact energy. That is, as heat-treatment temperature (900 to 950°C) increases, there is nearly a 20 HV decrease in hardness for annealing, a 55 HV decrease in hardness for normalizing, and about 160 HV drop in hardness for oil quenching. Whereas with an increase in temperature, impact energy increases by 10 to 15 J in each case. Holding time also has a similar effect on hardness and impact energy for each heat treatment.

Regression analysis

To further understand and evaluate the effect of heat-treatment temperature and holding time on hardness and impact energy, for each of the heat treatments, a multiple linear regression analysis was conducted.

The regression equations, with respective R-sq, R-sq (adj) and R-sq (pred) values, of hardness and impact energy for annealing are as shown in Equations 1 and 2:

$$\text{Hardness (HV)} = 577.7 - 0.4000 \text{ Temperature (c)} - 8.000 \text{ Time (h)} \quad \text{Equation 1}$$

$$\text{R-sq}=98.86\%; \text{R-sq (adj)}=98.48\%; \text{R-sq (pred)}=97.15\%$$

$$\text{Impact energy (J)} = -207.8 + 0.2533 \text{ Temperature (c)} + 10.667 \text{ Time (h)} \quad \text{Equation 2}$$

$$\text{R-sq}=98.83\%; \text{R-sq (adj)}=98.43\%; \text{R-sq (pred)}=96.80\%.$$

Regression Equations 1 and 2 can be used to evaluate the hardness and impact energy of the annealed AISI 4140 steel for the heat-treatment parameters within the range of values considered for current study.

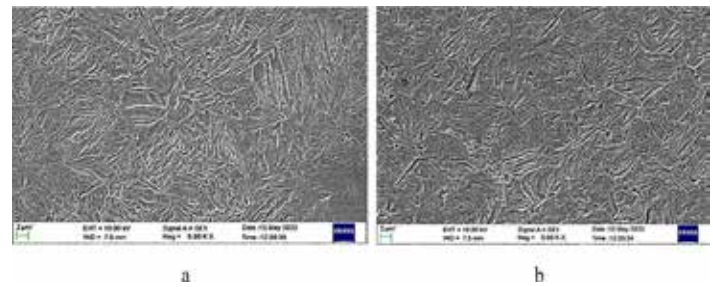


Figure 6: SEM images of AISI 4140 steel oil quenched at (a) 900°C for 2 hours, (b) 950°C for 2 hours.

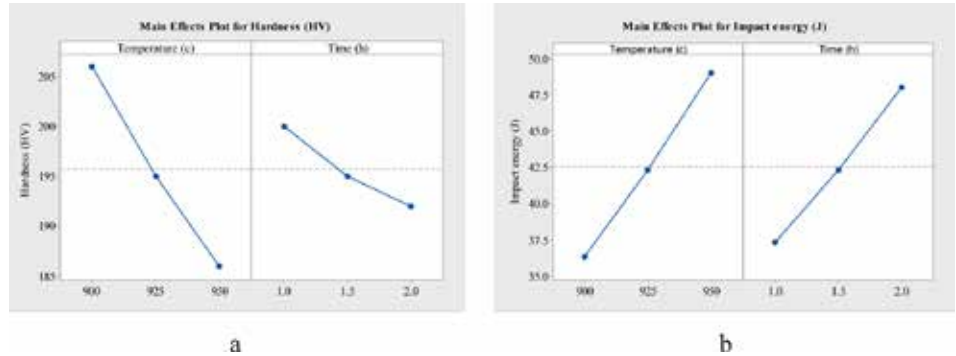


Figure 7: Main effect plot of (a) hardness and (b) impact energy, for annealing of AISI 4140.

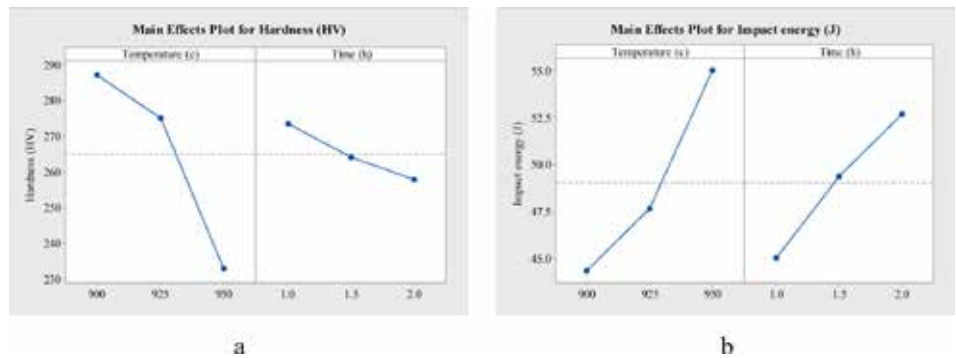


Figure 8: Main effect plot of (a) hardness and (b) impact energy, for normalizing of AISI 4140.

Similarly, for normalizing in Equations 3 and 4:

$$\text{Hardness (HV)} = 1288 - 1.080 \text{ Temperature (c)} - 15.67 \text{ Time (h)} \quad \text{Equation 3}$$

$$\text{R-sq}=88.05\%; \text{R-sq (adj)}=84.06\%; \text{R-sq (pred)}=72.43\%$$

$$\text{Impact energy (J)} = -159.8 + 0.2133 \text{ Temperature (c)} + 7.67 \text{ Time (h)} \quad \text{Equation 4}$$

Regression Equations 3 and 4 can be used to evaluate the hardness and impact energy of the normalized AISI 4140 steel for the heat treatment parameters which are within the range of values considered for current study.

And for oil quenching in Equations 5 and 6:

$$\text{Hardness (HV)} = 3416 - 3.180 \text{ Temperature (c)} - 43.7 \text{ Time (h)} \quad \text{Equation 5}$$

$$\text{R-sq}=95.04\%; \text{R-sq (adj)}=93.38\%; \text{R-sq (pred)}=86.66\%$$

$$\text{Impact Energy (J)} = -265.9 + 0.3133 \text{ Temperature (c)} + 4.00 \text{ Time (h)} \quad \text{Equation 6}$$

$$\text{R-sq}=94.98\%; \text{R-sq (adj)}=93.31\%; \text{R-sq (pred)}=88.04\%.$$

Regression Equations 5 and 6 can be used to evaluate the hardness and impact energy of the oil quenched AISI 4140 steel for the heat-treatment parameters within the range of values considered for current study.

| Heat treatment | Optimal temperature (°C) | Optimal time (h) | Hardness (HV) | Impact energy (J) | Composite desirability index (D) |
|----------------|--------------------------|------------------|---------------|-------------------|----------------------------------|
| Annealing | 900 | 2 | 202 | 42.5 | 0.6114 |
| Normalizing | 919.7 | 2 | 274 | 50 | 0.6284 |
| Oil quenching | 944.95 | 1 | 382.25 | 33.37 | 0.5243 |

Table 6: Response optimization results.

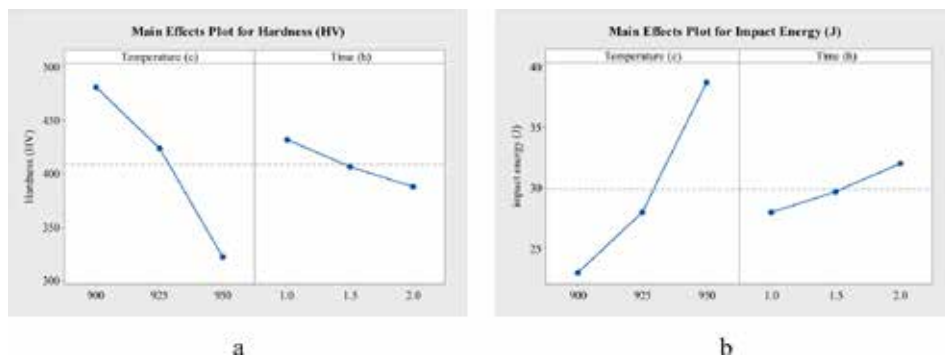


Figure 9: Main effect plot of (a) hardness and (b) impact energy, for oil quenching of AISI 4140.

Multiple response optimization

Multiple response optimization was done to get the optimal temperature and time for the best combination of hardness and impact energy for each heat treatment. This method of optimization determines process settings that simultaneously satisfy desired targets for multiple responses. Based on optimization results obtained through response surface optimization analysis, with an aim to get superior combination of hardness and impact energy, following combination of parameters, as shown in Table 6, were found to be optimal.

For annealing at the optimal temperature and time of 900°C and 2 hours, the best combination of hardness (202 HV) and impact energy (42.5 J) was obtained. For normalizing, the optimized values were found to be 919.7°C and 2 hours, for a hardness and impact energy values of 274 HV and 50 J respectively. Similarly for oil quenching, at 944.95°C and 1 hour temperature and time, the best combination of hardness (382.25 HV) and impact energy (33.37 J) was obtained. The composite desirability indexes, as shown in Table 6, indicate a balance between the two competing objectives. While the values are not close to 1 (ideal desirability), they reflect a feasible compromise between maximizing both mechanical properties.

CONCLUSION

The effects of annealing, normalizing, and oil quenching on the hardness and impact energy of AISI 4140 steel over an austenitization heat-treatment temperature range of 900-950°C and holding times of 1-2 hours, was studied. It was observed that for all the three heat treatments, hardness decreased, and impact energy increased with higher heat-treatment temperature and longer holding time, with the rate of hardness loss per °C/h highest for oil quenching (3.98 HV), followed by normalizing (1.42 HV) and annealing (0.54 HV). Based on the ANOVA results from Tables 4 and 5, we can infer that heat-treatment temperature has the greater influence, ranging from 57.87 to 93%, while holding time had a lesser influence (5.87 to 41%) on hardness and impact energy of the steel, across all three heat treatment conditions.

Based on the results obtained, the following conclusions were made:

» Oil quenching produced the highest hardness, averaging 120% higher than annealing and 58.63% higher than normalizing, but with the lowest impact energy. But as the heat-treatment temperature increased from 900°C to 950°C and holding time from 1 to 2

hours, hardness decreased at a rate of 3.98 HV/°C/h, and impact energy increased at a rate of 0.4 J/°C/h.

» Annealing had the lowest hardness but the highest relative gain in toughness, with impact energy increasing by 0.48 J/°C/h and hardness decreasing at a rate of 0.54 HV/°C/h.

» While normalizing offered balanced properties, with a 39% increase in hardness over annealing and a 17.5% increase in impact energy, hardness decreased at a rate of 1.42 HV/°C/h and impact energy increased by 0.4 J/°C/h with increase in heat treatment temperature and holding time.

» The ANOVA results show that heat-treatment temperature had a greater significant effect on the hardness (90.59%) and impact energy (93.05%) of the steel when it was subjected to oil quenching, while for annealing, it had the lowest, 85.51% for hardness and 57.87% for impact energy. While holding time had the most effect on hardness (13.92%) and impact energy (41.06%) for annealing.

» The optimization results showed that a temperature of 900°C and holding time of 2 hours gave the best combination of hardness and impact energy for annealed specimens, 919.7°C and 2 hours for normalized specimens, and 944.95°C and 1 hour for oil quenched specimens.

These findings show a trade-off between strength and toughness in heat-treatment design and provide quantitative guidance for selecting parameters to meet specific performance requirements. ⚡

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***SIMULATION-BASED PREDICTION
OF THE THERMAL PROCESS***

***EMISSION
MEASURED BY
PYROMETRY OF
316L STAINLESS
STEEL***

This publication presents a model for thermal simulation of the L-PBF process and a model for predicting the resulting thermal emission.

By TOBIAS BARANZKE, SEBASTIAN BREMEN, and FLORIAN EIBL

Laser powder bed fusion is a common additive manufacturing process in which metal powder is selectively melted by a laser. Meandering stripe hatching is often used in conjunction with constant process parameters such as laser power and scan speed. However, the exposure strategy and the part geometry influence the resulting melt pool. To compensate for these influences, closed-loop process control based on the thermal emission can be used. To enable closed-loop process control via pyrometry, an analysis of the measured thermal emissions is necessary, as the measurement spot of the pyrometry is larger than the melt pool. This article investigates how accurately the pyrometrically measured thermal emission can be predicted by a thermal simulation and how large the influence of the neighboring vectors is on the pyrometrically measured thermal emission. For this purpose, a thermal simulation model is first developed that considers the immediate environment (approx. 1 mm) of a single scan vector. Subsequently, a model is developed that predicts the thermal emission within the measuring spot of the pyrometer based on the simulated temperature. The results show the thermal emission prediction model provides an accurate prediction with an average deviation of approx. 4.5%. The evaluation of the influence of neighboring vectors also shows that in areas of small vectors, the pyrometrically measured thermal emission is caused by neighboring vectors by approx. 35%. In further investigations, the influence of the neighboring vectors in the setpoint of the controller is to be considered.

1 INTRODUCTION

For the production of L-PBF parts, meandering stripe hatching is often used in conjunction with constant process parameters such as laser power and scan speed [1-2]. The melt pool is influenced by the interaction of the energy input determined by the process parameters, the preheating, e.g. by the exposure strategy, and the part related heat dissipation, i.e. the part geometry [1, 3-7]. This leads to a geometry-dependent part quality. For example, [8] demonstrates a local elevation of 22 μm at turning points when using a meander exposure strategy. The local elevation is caused by the preheating of the previously exposed vectors. To compensate for these influences, closed-loop process control based on the thermal emission can be used.

Thermal emission refers to the heat radiation generated during the process, which is detected using pyrometry. Closed-loop process control offers a cost-effective and simple approach to automated parameter adaptation [9]. The AconityCONTROL (Aconity3D GmbH, Germany, Herzogenrath) control system compares the measured thermal emission with a constant reference value and regulates the resulting thermal emission via the laser beam power. The controller updates the control variable (laser power) at intervals of 10 μs [10]. The speed of the update in conjunction with the assumption that the pyrometrically measured signal can be used to evaluate the melt pool temperature makes closed-loop control appear promising, particularly with regard to increasing process robustness [10]. The investigations on several tracks show the preheating caused by the exposure strategy in particular can be mea-

sured via an on-axis pyrometer [9, 11]. The investigations of the thermal emission during the exposure of single vectors show the thermal emission allows conclusions to be drawn about the aspect ratio of the keyhole. A linear-proportional relationship can be demonstrated between the thermal emission normalized to the square of the beam diameter and the aspect ratio of the keyhole [12]. Investigations by Kavas et al. [10] show the use of a constant controller setpoint nonetheless leads to pore formation, especially in the case of small vector lengths. The spot size of the pyrometer in the L-PBF process is usually larger than the melt pool. The measuring spot size depends on the optical setup and therefore varies in the previous investigations. In most cases, however, the measuring spot is large enough to detect at least one neighboring melt track that has already been exposed. The neighboring melt tracks that have already been exposed are referred to as neighboring vectors.

One possible cause for the formation of pores when using process control is the thermal emission generated by neighboring vectors. In this publication, the influence of neighboring vectors is simulatively investigated in order to identify this as a source of error. Two models are developed for this purpose: The first model simulates the temperature field generated during the process. The second model is then used to predict the thermal emission, which is measured using pyrometry. Numerous studies have already presented simulation models for the L-PBF process [13]. However, there is currently a lack of models that predict or examine in more detail the thermal emission measured using pyrometry. The methodology section first describes the manufacturing process used to evaluate the simulation and calculate the emissivity. The two models are presented in the following sections. The results of the investigation are described and discussed in Section 5.

2 METHODOLOGY

Two models will be developed that enable the prediction of thermal emission. To evaluate the accuracy of the prediction and to calculate the emissivity, test specimens are built and the resulting thermal emission is measured via an on-axis pyrometer. The specimens are cylindrical with triangles in the center (see Figure 1), resulting in areas with small vector lengths.

The samples are manufactured on an L-PBF machine AconityMIDI (Aconity3D GmbH, Germany, Herzogenrath). The AconityMIDI is equipped with a 1,200W AFX-1000 laser (nLIGHT, United States, Washington). The samples are made from 1.4404 powder "m4p™ 3161" (m4p material solutions GmbH, Austria, Feistritz i. R.) with an average grain size of 45 μm . The thermal radiation generated in the process is detected in the wavelength range from 2.0 μm to 2.2 μm with a measuring frequency of 100 kHz using a customized non-linearized KG 740-LO pyrometer (Kleiber Infrared GmbH, Unterwellenborn, Germany). Due to the lack of linearization, the emissivity set on the pyrometer corresponds to a division of the measurement signal by the emissivity. To maximize the measurement signal, the emissivity is set to 0.1, which corresponds to the minimum adjustable emissivity. The build platform is preheated to a temperature of 100°C to produce

the test specimens. The process parameters used for production are listed in Figure 1. The samples are exposed in sequence (part 1 to 12) against the inert gas flow in order to reduce the influence of spatter. A meandering stripe hatching is used as the exposure strategy, which is rotated by 33° layer by layer. Vector directions with an angle of less than 45° to the shielding gas flow are omitted in order to reduce the interaction of the laser beam with the metal vapor, cf. [14].

3 THERMAL SIMULATION MODEL

For the thermal simulation, a model is developed that only considers the environment of an exposure vector. This approach makes it possible to map pre-heating effects due to the exposure strategy while keeping the numerical effort to a minimum. The model is programmed in Python and is based on the finite difference method. Figure 2a shows an example of the calculation area for different vectors. The simulated scan vector is shown in red. The size of the calculation area depends on the length of the exposure vector. The origin of the calculation area is always at the starting point of the exposure vector, while the exposure direction is the X-axis of the calculation area. This means the calculation area rotates relative to the part depending on the orientation of the exposure vector. The advantage of the described calculation area is that the meshing only has to be carried out once, as the meshed grid is only shifted or rotated. A structured grid with different element sizes in the Z-direction is used for meshing. Figure 2a shows that, in the area of the laser-material interaction, the mesh is finest in the Z-direction (element height = layer thickness). From a given number (n_1) of elements, the element size in the Z-direction is doubled. The number of elements in the Z-direction is $n_z = 12$. The element size is doubled after $n_1 = 6$. The element size in the X- or Y-direction corresponds to the track spacing (100 μm). This corresponds to the largest possible element size for mapping the exposure vectors. The number of elements in the Y-direction is $n_y = 21$, and the number of elements in the X-direction is determined by the length of the longest exposure vector of a layer to be simulated and a specified edge distance of seven elements. The part layers of the part to be simulated are simulated independently of each other, i.e. preheating by already exposed layers is neglected. To simulate a layer, the vector information is loaded from a CLI (common layer interface) file. The element state (powder or solid) is also assigned based on the CLI file. When starting the simulation of a layer, the temperature of all elements is set to the preheating temperature (see Section 2). As a boundary condition, it is assumed that the global part temperature corresponds to the preheating temperature, so that the side surfaces and the bottom surface of the calculation area are set to the preheating temperature as a constant boundary condition (see Figure 2c). The upper surface of the calculation area borders on the shielding gas flow. In order to map the shielding gas flow in the simulation, the mean heat-transfer coefficient with forced convection is calculated for a longitudinally flowing flat plate with laminar boundary layer according to [15]. It is assumed the shield gas has a temperature of 60°C, and the characteristic length l is equal to the diameter of the substrate plate (170 mm).

The calculation of the material values is based on references [15-21]. Due to the melt pool dynamics, which cannot be represented by the purely thermal simulation, more heat is dissipated from the melt pool (cf. [22]). In order to take the influence of Marangoni convection into account in the thermal simulation, the thermal conductivity within the melt can be artificially increased by a correction factor $\gamma = 3$ [23] (cf. [8]). In the simulation model, the enthalpy of melting is neglected for the purpose of simplifying the model. However, this can be incorporated into the specific heat capacity in subsequent investigations. The thermal conductivity of the powder λ_p is calculated according to the equation by Meredith and Tobias [24]. To calculate the



Figure 1: Specimen arrangement, specimen geometry and process parameters.

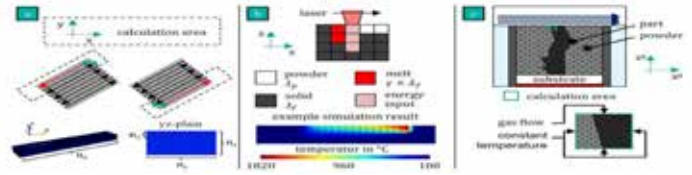


Figure 2: (a) mesh and calculation area (b) modeling of the heat source (c) boundary conditions.

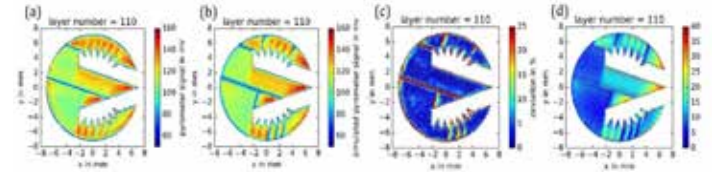


Figure 3: (a) measured thermal emission (b) simulated thermal emission (c) deviation (d) signal component of the neighboring vectors.

thermal conductivity of the powder, the volume ratio φ of solid to gas is estimated at 70%. The specific heat capacity c_g and the density ρ of the powder are calculated from the volume ratio of the solid and gas properties. To map the energy input by the laser, a cuboid volume with a constant heat flow is used as the heat source, cf. [25]. The power density W is calculated according to $W = P_1 \mu_l / h^2 \Delta z_s n_w$ with the laser power P_1 , the absorption coefficient μ_l , the track spacing h , the layer thickness Δz_s , and the number of elements n_w . The number of elements n_w represents the depth of the melt pool in the Z-direction. The energy input takes place in n_w elements in the Z-direction. Figure 2b shows the heat source for $n_w = 3$ and the simulated temperature of an exposure vector in a cutaway drawing. The elements where the energy input occurs are shaded. The absorption coefficient is assumed to be 60% and indicates the proportion of the laser power that is absorbed by the molten pool, cf. [25].

4 PREDICTION OF THERMAL PROCESS EMISSIONS

To predict the thermal emission, the emission of the elements located in the measuring spot of the pyrometer is calculated. The size of the measuring spot is determined by scanning an aperture (diameter = 1 mm) with a radiation source underneath. The determined measuring spot of the pyrometer is 0.94 mm. The manufacturer of the pyrometer specifies the relationship between output value and temperature for linearization. Assuming that each element within the measurement spot is included in the measurement signal to the same extent, the output value is calculated in relation to the measurement spot area. This relationship is used to calculate an output value field from the simulated temperature field. This output value field is then multiplied by the emissivity of the material and divided by the emissivity set on the pyrometer (see section 2). The sum of the output values gives the predicted signal of the pyrometer. Two emissivity values are used to predict the thermal emission, the first for temperatures below 1,000°C and the second for temperatures above 1,000°C. To determine the emissivities, both emissivities are varied in a range from 0 to 1 for the prediction of the emission of 15 layers and the deviation from the measured signal is determined. The combination of emissivities that results in the smallest deviation is used to predict the thermal emission. To calculate the deviation between the predicted and measured signal, the emission of all built-up samples is averaged and reduced to the resolution of the simulation. To reduce the resolution, the measured values within an element are averaged.

5 RESULTS AND DISCUSSION

The averaged measured thermal emission signal for an exemplary layer 110 is shown in Figure 3. The emissivities that lead to the smallest deviation between the predicted and measured signal are: $\varepsilon_{\varphi < 1,000^\circ\text{C}} = 0.482$ and $\varepsilon_{\varphi > 1000^\circ\text{C}} = 0.131$. A comparison with values from the literature shows that, despite differing absolute values, the ratio is of a similar magnitude: $\varepsilon_{\varphi=700^\circ\text{C, sandblasted}} = 0.7$ and $\varepsilon_{\varphi=1600^\circ\text{C, } \varphi < 1800^\circ\text{C}} = 0.28$ [26]. The prediction of the thermal emission provides an accurate prediction with an average deviation of 4.5% (9.4 mV) for layers 100 to 150. The deviation is greatest at the edges of the stripes. This deviation is probably due to the neglect of the pre-heating of already exposed strips. With each shift of the calculation area, the preheating temperature is assigned to the elements that lie outside the calculation area of the last time step. Particularly in the case of step vectors, this procedure means that local part overheating is no longer considered. Despite the existing deviation, the thermal simulation can map the preheating effects caused by the exposure strategy and enables a prediction of the thermal radiation generated in the process. Figure 3 shows the signal component caused by the thermal emission of neighboring vectors. To calculate the proportion of neighboring vectors, the signal proportion of the area with a temperature below 1,000°C is evaluated in a simplified manner. The signal component increases to approx. 35%, especially in the area of small vectors. The influence of neighboring, not yet completely cooled vectors on the measured thermal emission is possibly the reason for the observation that the porosity increases when using a closed-loop process control.

6 CONCLUSION AND FUTURE WORK

This publication presents a model for thermal simulation of the L-PBF process and a model for predicting the resulting thermal emission. With both models, the resulting process emission can be predicted with an average deviation of 4.5%. Since the simulation presented has only been experimentally validated for one material and one set of parameters, further investigations involving a comprehensive uncertainty study must be carried out. For example, it can be investigated whether the prediction of thermal emission is possible with similar accuracy when the laser power is varied. Furthermore, it is shown that a part of the pyrometrically measured thermal emission is caused by neighboring vectors.

However, this conclusion is based solely on a simulation study, which is why further investigations must be carried out to confirm this assumption. One possibility would be to investigate the melt pool geometry in the area of small vectors by micrographs and compare it with the measured increase in thermal radiation. However, predicting the thermal emission to define a variable controller setpoint seems promising. A variable controller setpoint could consider the thermal emission of neighboring vectors in advance. This would prevent excessive power reduction and enable closed-loop process control, which can lead to higher part quality. In addition, a direct adjustment of the laser power based on thermal simulation will be further investigated. As part of this investigation, a sensitivity analysis will be carried out to evaluate the influence of the assumptions made on the simulation result. It may be possible to achieve a significant reduction in part defects by using a hybrid simulation-based control concept. ♡

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COMPANY PROFILE ///

W.H. KAY COMPANY

90 YEARS OF SERVING THE INDUSTRIAL HEAT-TREATING INDUSTRY

A car bottom
furnace in
stock at W.H.
Kay. (Courtesy:
W.H. Kay)

For almost a century, W.H. Kay Company has designed and sold new burner systems for industrial ovens and heat-treating furnaces.

By **KENNETH CARTER**, Thermal Processing editor

Consistency can be a crucial component in the world of industrial heat treating. That ability to stay reliable and proven is an important part of what's kept W.H. Kay Company supplying burner systems and controls for heat-treating furnaces to its customers for almost a century.

"This is our 90th year," said Michael Kay, president of W.H. Kay Company. "The company was started in 1936 representing Eclipse Combustion, which is a burner manufacturer. The company sold burners and furnaces in the 1940s to support the war effort."

REPRESENTING QUALITY MANUFACTURERS

With W.H. Kay Company entering its 10th decade, it's still going strong designing and selling burner systems, according to Kay. The company also buys, sells, and trades used industrial ovens and heat-treating furnaces and has more than 200 units in stock in its warehouse in Cleveland, Ohio.

"We've represented Eclipse for 90 years, and when Eclipse was bought by Honeywell, we now continue to represent Eclipse, Maxon, and Kromschroder," he said.

The wide variety of equipment W.H. Kay offers includes:

- » New aluminum drop bottom furnaces and horizontal aluminum quench furnaces (any size).
- » New walk-in ovens of any size – both gas-fired and electric.
- » New burner systems from Maxon, Eclipse, and Kromschroder.
- » Batch ovens.
- » Belt ovens.
- » Box furnaces.
- » Car-bottom furnaces.
- » Pit furnaces.
- » Aluminum drop bottom furnaces.
- » Vacuum Furnaces.
- » Atmosphere generators.

STAYING NEEDED

Going strong for 90 years means W.H. Kay has been able to both stay constant while changing with the times in order to stay relevant and needed by its customers, according to Kay.

"We try and be there with expertise and solutions for both OEMs and 'end-user' customers," he said. "We also buy and sell used heat-treat equipment, and test them out prior to shipping. We're basically manufacturer reps selling burner systems and controls."

W.H. Kay also specializes in aluminum heat treat, both drop-bottom furnaces and horizontal clench furnaces, but on top of what the company offers, it is vital that it be both visible and available when needed, according to Kay. "You have to know your customers and you have to treat people right; otherwise, they won't come back to you," he said. "We have a ton of repeat customers. When we sell something, they're coming back maybe in 10 years."

As with most things, each issue brought to W.H. Kay by its customers offers its own set of unique challenges, according to Kay.

WORKING WITH THE CUSTOMER

"Every issue is different, but they come to us for process heating solutions," he said. "For example, somebody may want to get into an oil quench line, and we will look around for one, or we might have one in stock, then we'll sell them the whole line if we have it available."

W.H. Kay is also experienced in converting electric furnaces to gas, according to Kay. "We can design a burner system that saves the customer a lot of money going from electric to gas firing," he said. "Converting from electric to gas will let a customer keep the same performance while saving them up to 60 percent. Even though the cost of fuel over the years has gone up and down for both electric and gas, gas is still more economical overall." Kay attributes multiple big sales through the years as major accomplishments, but the 90-year mark still remains the most special to the company and its employees. "Reaching 90 years in business is probably our biggest achievement, which is probably 0.00001 percent of companies that go 90 years," he said. "There are very few companies older than us."

SUCCESS FACTORS

Being respectful and courteous are just as important as expertise for this long-lived company, according to Kay. "It means just treating people right and knowing what you're doing and then standing behind it," he said. "That helps with repeat business. We've been doing jobs for some of the same companies for 60 years." W.H. Kay may not be as big as other heat-treat distributors, but its tenacity in the industry continues to make it viable, according to Kay.

"We have three sales guys, so we're not a big outfit, but we do have a 30,000-square-foot warehouse where we keep furnaces and ovens in stock for customers," he said.

THE NEXT PHASE

Having been successful for such a long time, Kay said he doesn't see much need to fix what's not broken as W.H. Kay continues into the future.

"You've got to keep in the flow of things, really; we haven't changed our selling philosophies or even what we're selling in 50 years," he said. "We're still selling furnaces, burners, valves, flame safety — everything that goes into a process heating system." 🔥

MORE INFO www.whkay.com



A horizontal aluminum quench furnace sold by W.H. Kay. (Courtesy: W.H. Kay)

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Q&A /// INTERVIEW WITH AN INDUSTRY INSIDER



DR. LESLEY FRAME /// 2026-2028 PRESIDENT /// IFHTSE

“My goal is to leverage what we already have and incrementally expand and build IFHTSE to be an even greater resource for the heat-treat community.”

How long have you been involved with IFHTSE (International Federation for Heat Treatment and Surface Engineering) and how did you get involved?

I've been on the board two years already. I was on the board as part of the executive committee as a vice president and now president, and then I'll be past president after my two-year term. I've helped out with various events in the past, including serving as co-chair for the Thermal Processing in Motion conference in Spartanburg, South Carolina, in 2018.

What do you hope to accomplish as president?

There are opportunities for us to pull in new members. We have a very strong European contingent. We have a very strong East Asian contingent, and we have, I'd say a moderately strong North America contingent. Each of these areas is active in both the conference planning and in terms of the leadership participation in IFHTSE. What I'm hoping for is that we get representation from some of the other countries around the world where there's a very strong heat treating and surface engineering presence not yet connected to IFHTSE. This would be, for example, building our connections to researchers, professional societies, and companies in India, and also pulling in collaborations from some of the organizations in Canada and also from South America.

Being able to broaden our global network is one of the goals. Now, of course, since I'm only president for two years, doing all of that in two years won't be possible. My goal is to leverage what we already have and incrementally expand and build IFHTSE to be an even greater resource for the heat-treat community.

What challenges do the heat-treating and surface engineering industry face in the next two years and beyond?

I'm an associate professor in material science engineering. I spent some time in industry, and I like to collaborate with industry on real-world problems, but my perspective is highly academic at this point, meaning I see the challenges from the teaching and the research perspective. What I see as one of the challenges is workforce development — one of the key things that I think has been a challenge for decades.

I've spent a lot of time with the heat-treating society within ASM, and one of the conversations that always comes up during board meetings is: How do we pull in students? How do we pull in young professionals? How do we get people attracted to heat treating? That is always a challenge, and it requires constant effort to keep meeting that challenge. It's not a problem that we solve once, and we're done. It's a perennial issue. Some of the things that we can do as an organization is help support students and these early career profes-

sionals to attend the conferences, to become involved in different aspects of leadership — of the professional societies that are part of IFHTSE — to give them opportunities to network and learn who the key players are, and to learn how they can get involved with solving big scale industry problems.

IFHTSE does a number of things to help promote that, and maintaining and even building on that would be great over the next couple of years. Some of the things we already do well include having speaking awards and poster awards and travel grants for students. We try to encourage students and young professionals to attend the conferences by offsetting the financial burden for them to attend. We also try to promote their research efforts at the conferences, drawing attention to what it is they're doing. It helps ignite conversations among the students and the industry professionals.

That's on a global scale with the young professionals?

Yes. We have our conferences around the world, and we'll have travel grants for students to go to conferences in China or in Cologne for our World Congress next year. These opportunities are promoted through IFHTSE.

Do you want to expand on how IFHTSE is bringing in other countries?

It is not just a matter of saying: “Do you want to join? Good. You've joined.” Being part of this federation is a little bit different than being part of a professional society. The IFHTSE is a collection of societies, and the ways we can involve other countries is to first identify what professional societies or companies or academic institutions could be members, and then determine the value proposition for them to gain membership within IFHTSE. In other words, making sure it's clear to them that, when they're paying dues to IFHTSE, they know what they are getting out of it, and how we can make sure it's a two-way collaboration. That takes more dialogue and relationship building, which is part of the work that we've already begun.

What can members expect from this year's World Congress?

Every year, the World Congress is designed to have in-depth technical presentations, symposia, and panel discussions, and, in some cases, workshops that pull together industry professionals with academics so we can learn from each other and help address or discuss and identify the big heat-treat and surface-engineering challenges. The final program isn't released yet, but every year our World Congress program is packed with these technical presentations. 🌟

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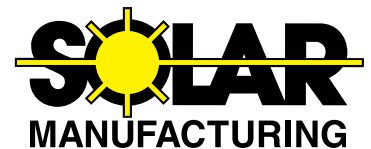
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