Technologies and Processes for the Advancement of Materials

Thermal processing

ISSUE FOCUS ///

INDUCTION HEATING / QUENCHING

DETERMINING THE CAUSE OF CRACKING

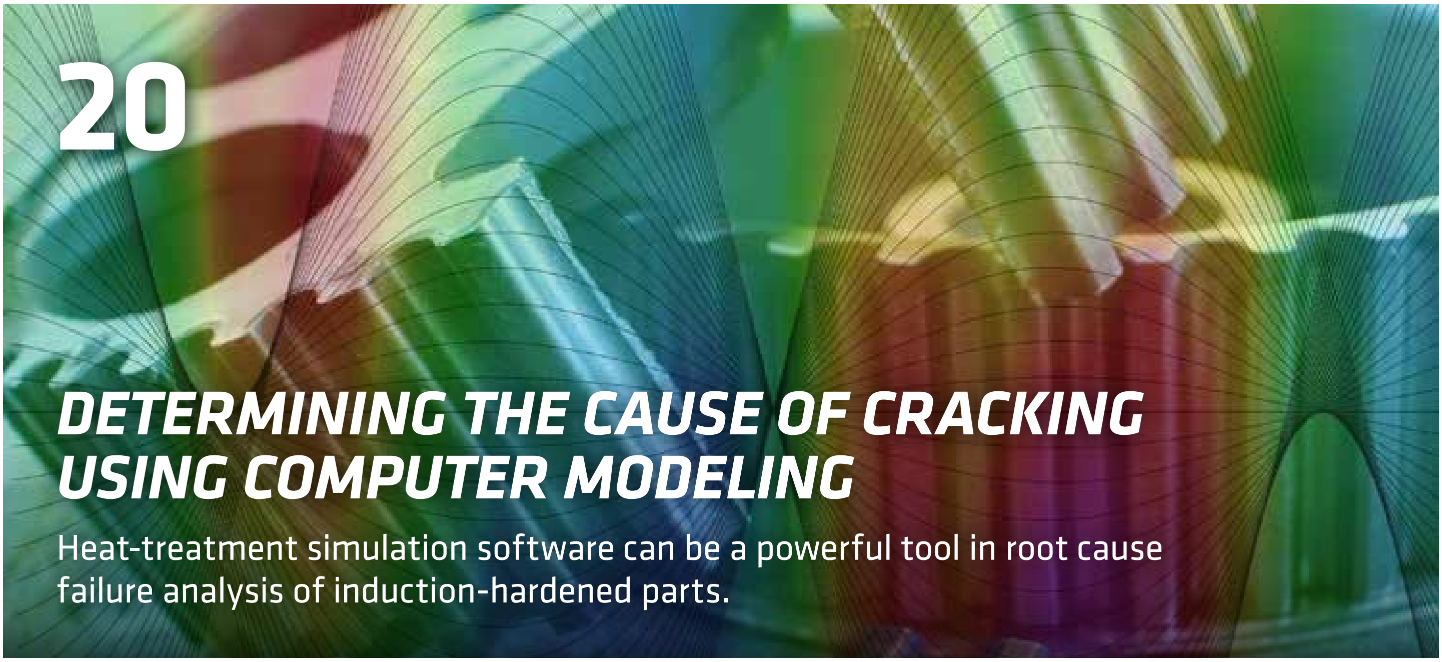
USING COMPUTER MODELING

COMPANY PROFILE ///

JOFRA Calibration

JULY 2020
thermalprocessing.com

CONTENTS ///



COVER PHOTO: SHUTTERSTOCK (3) / ILLUSTRATION BY RICK FRENNEA

DEPARTMENTS ///

JULY 2020 VOLUME 9 / NUMBER 7

Thermal Processing is published monthly by Media Solutions, Inc., 266D Yeager Parkway Pelham, AL 35124. Phone (205) 380-1573 Fax (205) 380-1580 International subscription rates: $105.00 per year. Postage Paid at Pelham AL and at additional mailing offices. Printed in the USA. POSTMASTER: Send address changes to *Thermal Processing* magazine, P.O. Box 1210 Pelham AL 35124. Return undeliverable Canadian addresses to P.O. Box 503 RPO West Beaver Creek Richmond Hill, ON L4B4R6.

FROM THE EDITOR ///

We take your message farther than anyone

If the current global climate has taught us anything, it's shown us that the industry is made up of an amazing network of companies that are changing and adapting in order to keep those furnaces and ovens hot and running.

Has it been easy? The answer to that would be an emphatic "no." But it's been a necessary task that has proven the industry's mettle — or should that be metal?

Thermal Processing wants you to know that we are here for you, and in ways that continue to make us your No. 1 source for heat-treating news and information on a variety of platforms.

What do I mean by that?

Thermal Processing is the only monthly heat-treat magazine that presents this information in print as well as online.

What does that mean for you?

It means your information — whether it's an eye-catching advertisement or an intelligently written article presented by an industry expert — is not only visible and available on the internet through our website and social media, but it also enjoys a long shelf life as a physical printed vehicle in offices and homes around the country.

That's good news for your audience in search of the very services and products that you can provide every day. And with the world trying to cope with economic and medical hardships, the deep reach *Thermal Processing* can provide is more important than ever.

With that in mind, I hope you find the articles in our July issue of interest as you work to get back to normal or are still busy navigating a new normal.

Our July issue takes a deep dive into induction hardening and quenching.

In our Focus section, *Thermal Processing* frequent contributor and columnist Justin Sims, along with his colleague, Charlie Li, takes a look at determining the cause of cracking of an induction hardened component using computer modeling.

On the subject of quenching, you'll find an article from Thomas Hart and Dr. Maciej Korecki where they discuss the new process of 4D high-pressure gas quenching. In the piece, you'll discover how 4D HPGQ is a leap in performance vs. press quenching, allowing for significant improvements to the quenching process.

And make sure you check out our Q&A with CeraMaterials' Jeff Opitz. The company has recently launched a new website exclusively devoted to graphite insulating products. It's a novel venture that Opitz expects to streamline how customers can take advantage of CeraMaterials' graphite product line and more.

That's just a taste of what July's issue has in store for you.

Thermal Processing is here to serve you. With that in mind, if you have any suggestions or would like to contribute, please contact me. I'm always looking for exciting articles to share.

Stay safe and healthy out there, and, as always, thanks for reading!

KENNETH CARTER, EDITOR
editor@thermalprocessing.com
(800) 366-2185 x204

CALL FOR ARTICLES Have a technical paper or other work with an educational angle? Let Thermal Processing publish it. Contact the editor, Kenneth Carter, at *editor@thermalprocessing.com* for how you can share your expertise with our readers.

Thermal processing

David C. Cooper
PUBLISHER

EDITORIAL

Kenneth Carter
EDITOR

Jennifer Jacobson
ASSOCIATE EDITOR

Joe Crowe
CONTRIBUTING EDITOR

SALES

Dave Gomez
NATIONAL SALES MANAGER

Ben Keaten
REGIONAL SALES MANAGER

CIRCULATION

Teresa Cooper
MANAGER

Jamie Willett
ASSISTANT

DESIGN

RIck Frennea
CREATIVE DIRECTOR

Michele Hall
GRAPHIC DESIGNER

CONTRIBUTING WRITERS

HELMUT CLEMENS
STEPHAN HAFENSTEIN
THOMAS HART
LEONHARD HITZLER
SHAUN KIM
DR. MACIEJ KORECKI
CHARLIE LI
D. SCOTT MACKENZIE
FRANCISCA MENDEZ MARTIN
MARKUS MERKEL
ANDREAS ÖCHSNER
JUSTIN SIMS
ENES SERT
EWALD WERNER

Media solutions

PUBLISHED BY MEDIA SOLUTIONS, INC.
P. O. BOX 1987 • PELHAM, AL 35124
(800) 366-2185 • (205) 380-1580 FAX

David C. Cooper
PRESIDENT

Teresa Cooper
OPERATIONS

The new BeaverMatic IQF is gas-fired using single ended radiant tube (SER) burners for optimum efficiency. (Courtesy: Premier Furnace/BeaverMatic)

Heat treater installs Premier Furnace/ Beavermatic IQF

A technically and scientifically-progressive commercial heat-treating company in Canada has installed a Premier Furnace/BeaverMatic internal quench furnace (IQF) and a Premier Furnace/BeaverMatic spray/dunk washer to meet customer demands for improving product processing and production cycles.

The new BeaverMatic IQF Furnace, with a work area of 36” wide x 48” long x 40” high, was purchased for hardening 4,000 pounds (gross), and an operating temperature of 1,850°F. The unit is gas-fired using single ended radiant tube (SER) burners for optimum efficiency.

For precision control of temperature and furnace operations, a PLC with full-screen HMI along with process control software are being used for temperature, atmosphere, sophisticated recipe programming, and oil quenching. Ethernet communications, built-in data logging, and an expandable I/O, are among the features. Complementing the process control is a data acquisition/control system, which will provide the customer with quick access to real-time and historical data throughout the plant.

The customer, as an environmentally-conscious heat treater, chose eco-friendly products and methods to minimize the environmental impact. This internal quench furnace uses approximately 4,000 gallons of oil while meeting the requested heating and cooling requirements. The new furnace also incorporates a quench oil centrifugal filtration system.

In tandem, the Premier Furnace/BeaverMatic spray/dunk washer, with identical workload capacity, will accommodate and remove most quench oils before the next process. Premier Furnace/BeaverMatic constructs the spray/dunk washer out of stainless steel. Its agitation and robust design exceeds most competitors’ designs.

MORE INFO www.premierfurnace.com
www.beavermatic.com

Joe Conyers joins sales team at Graphite Metallizing

Graphite Metallizing Corporation, the manufacturers of self-lubricating Graphalloy® bushing materials for pumps and process equipment, has appointed Joe Conyers as territory sales manager for California, Arizona, and Nevada.

Conyers holds an aerospace engineering degree from the U.S. Naval Academy. With more than 30 years of experience in the bearing industry, he previously served as SKF’s United States and Canada sales manager for maintenance products. He will be based out of his office in California.

Joe Conyers

“Joe brings valuable bearing experience to our sales team,” said Eben Walker, general manager of Graphite Metallizing. “His bearing application experience in some of the toughest environments will help engineers apply Graphalloy to their most difficult applications.”

Graphite Metallizing Corporation of Yonkers, New York has been solving tough bearing problems for more than 100 years. The company began in 1913 when two engineers developed a method for putting mol-

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.

ten metal into carbon to create a new material called Graphalloy, a graphite/metal alloy.

Used in the manufacture of bushings, bearings, and other components for machinery and process equipment, Graphalloy can be the solution to the toughest bearing, bushing, thrust washer, cam follower, or pillow block bearing design problem. It is available in more than 100 grades with specific properties that meet a wide range of engineering solutions and specifications. FDA accepted grades of Graphalloy are available for use in food service equipment. NSF® International has certified two grades of Graphalloy material for use in municipal well pumps and water treatment plant applications

Graphalloy bearings have operated for 20 years, and longer in some applications. Standard designs are available but most Graphalloy products are custom-designed to the unique requirements of the specific application. Graphite Metallizing Corporation is ISO certified.

MORE INFO www.graphalloy.com

The CQI-9 controls package includes data acquisition, preventative maintenance alerts, remote connectivity, furnace parameter trending, and temperature deviation alarms. (Courtesy: Gasbarre)

Gasbarre upgrades brazing furnace for CQI-9 production

Gasbarre Thermal Processing Systems recently rebuilt and shipped a 24-inch, four zone continuous mesh-belt brazing furnace for an automotive parts supplier in Mexico.

The rebuild included a new 330 stainless steel muffle, new silicon carbide heating elements, new cooling sections, and new furnace controls to meet CQI-9 requirements. The CQI-9 controls package includes data acquisition, preventative maintenance alerts, remote connectivity, furnace parameter trending, and temperature deviation alarms. Gasbarre was chosen as a partner for its brazing expertise, unique controls package, and ongoing service and support of the customer in Mexico.

With locations in Plymouth, Michigan; Cranston, Rhode Island; and St. Marys, Pennsylvania, Gasbarre Thermal Processing Systems has been designing, manufacturing, and servicing a full line of industrial thermal processing equipment for nearly 50 years. Gasbarre's product offering includes batch and continuous thermal processing equipment for both atmosphere and vacuum applications as well as a full line of alloy fabrications, replacement parts, and auxiliary equipment, which consists of atmosphere generators, quench tanks, washers, and charge cars. Gasbarre's equipment is designed for the customer's process by experienced engineers and metallurgists.

MORE INFO www.gasbarre.com

The new Solar Manufacturing HFL-7496-EQ vacuum furnace will be one of the largest horizontal vacuum furnaces in the UK. (Courtesy: Solar Manufacturing)

Magnetic Shields orders second vacuum furnace

Magnetic Shields Ltd. of Kent, England, and Solar Manufacturing have had a strong partnership since 2016. In this time, Solar Manufacturing has engineered one vacuum furnace and has been commissioned to design and build a second furnace. This new furnace will be one of the largest horizontal vacuum furnaces in the U.K.

The new HFL-7496-EQ vacuum furnace, being built with a SolarVac® Polaris control system, will be designed to accommodate loads up to 48" wide x 48" high x 96" deep, (1,220 x 1,220 x 2,440mm) with a maximum weight of 5,000 pounds (2270 kgs). Operating at a vacuum level of 10-5 Torr, this new furnace will be able to reach temperatures up to 2,400°F (1,315°C). It will feature a partial pressure hydrogen gas process and an external quench system designed for negative pressure quenching.

Rick Jones, VP of international sales at Solar Manufacturing, said, "Solar Manufacturing is very pleased to be selected as the supplier to further support Magnetic Shields in leading the production of equipment for the medical industry and other high technology applications, specifically, high performance large magnetic shields and low field shielded rooms."

Magnetic Shields Ltd. Director Colin Woolger said, "Magnetic Shields is delighted to order our second vacuum furnace from Solar Manufacturing. The new furnace will enable us to more than double the maximum size of shields we can now produce in one piece and also increase the general heat-treatment capacity for our growing company. This order was awarded, in no small part, due to the superb reliability of our existing Solar Manufacturing furnace which has revolutionized the consistency and quality of our magnetic heat-treatment process, a key stage in the manufacture of all of our shielding products. We look forward to the new furnace arriving later this year."

Solar Manufacturing designs and manufactures a wide variety of vacuum heat-treating, sintering, and brazing furnaces.

MORE INFO www.solarmfg.com

Liberty Wire upgrades continuous furnace lines controls

Super Systems, Inc. recently completed a nitrogen-methanol controls upgrade for a continuous furnace line at Liberty Wire in Johnstown, Pennsylvania.

The scope of the project included a new control system and panel for a continuous annealing furnace line for processing coiled wire products. The SSI Matrix control system was incorporated to control the automated flow and mixing of the process gases. SSI HMI and eFlo 2.0 meters were also integrated to provide Liberty with the latest in hardware, software, and communications technology.

SSI Controls Matrix. (Courtesy: Super Systems Inc.)

Mike Cassidy, the Liberty Wire controls analyst, led the installation with SSI project engineers.

"I'm very pleased with SSI and the new system. Can't think of any aspect of the whole deal that I could find fault with or complain about … they are top-notch. I'm looking forward to working with them in the future," he said.

Liberty Wire Johnstown produces and provides a wide variety of steel wire and rod products for industry. The company focuses on market segments where metallurgical quality is the differentiating factor. Their customers are primarily in the transportation and construction industry segments, but also supplies products for capital goods, energy, and consumer products.

Super Systems Inc., based in Cincinnati, Ohio, has been developing and manufacturing products for the thermal-processing industry since 1995. SSi's products include probes, analyzers, flow meters, controllers, software solutions, and engineered systems. With more than 100 years of combined experience, SSi continues to satisfy industry demands with innovative technology, enabling customers to be more efficient and to produce higher quality products.

MORE INFO www.libertyhousegroup.com
www.supersystems.com

Aerospace manufacturer gets box furnaces

L&L Special Furnace Co., Inc. has delivered three multipurpose GS2026 bench-mounted box furnaces used to test high-temperature aerospace fasteners.

The fastener manufacturer in Pennsylvania now has five GS series furnaces at its facility.

The new model GS2026 has internal dimensions of 18" wide by 12" high by 24" deep. It has an operating voltage of 208, 220, and 240 volts single phase, 60 or 50 hertz.

L&L Special Furnace's GS2026 box furnace will be used for general heat treatment, laboratory work, ceramics, and other thermal applications. (Courtesy: L&L Special Furnace Co., Inc.)

Included is a spring assist vertical lift door that allows for effortless loading and unloading even at high temperatures. The control is an industrial control system that includes a Eurotherm temperature control, overtemperature protection, and a recirculation fan for uniformity.

The furnace is constructed from 3-inch lightweight IFB firebrick, backed up with two inches of board insulation. The elements are supported in hard ceramic element holders. These provide long element life and are easily replaced.

The elements are on both sides and at the top and bottom, which enables equal heat distribution from all sides. This element distribution has proven with the industrial control option to achieve a uniformity gradient of ±10°F.

Standard units include a sheathed thermocouple, a slot in the door for access into the furnace, a bench-mounted powder-coated CNC machined case, ceramic hearth plate with standoffs, a door limit switch that turns the power to the elements off if the door is opened, an on/off toggle switch with control fusing, and a power plug. An optional angle iron stand and vent kit are available.

The furnace is shipped by common carrier on a skidded carton with foam-in-place packaging. L&L has some units in stock available for same-day shipment. Units with control upgrade or fan option usually ship within one to three weeks.

L&L offers the GS2026 as a choice for general-purpose heat treating as well as high-tech industrial applications.

MORE INFO www.llfurnace.com

Custom Steel Fabricators invests in welding solutions

Custom Steel Fabricators, Inc. consists of two workshops and an approximately 50,000 square feet working area in Columbia, Tennessee. The company serves a variety of industries such as power, chemical, cement, aluminum, and carbon products with work experience of all 300 series of stainless steels, duplexes, and 6 percent moly grades, as well as most nickel alloys.

Custom Steel Fabricators, Inc. employs about 40 people and has steadily grown its scope of work throughout the years — which is one of the reasons the company decided to invest in PEMA solutions. After the first interactions in 2018, Pemamek delivered the first PEMA solutions to Custom Steel Fabricators, Inc. during the spring of 2020.

"As the scope of our work and our customer base grew, one of the challenges we faced in our fabrication process was the fitting and welding of large-diameter shells. The use of turning rolls and a welding manipulator with SAW process assisted, but as the required sizes kept growing, these solutions proved to be inadequate," said Tony Sciotto, the president of Custom Steel Fabricators, Inc.

To tackle the challenge and offer various production benefits, Pemamek delivered PEMA Assembly Station TW5000-25 with side support arms and integration to PEMA MD 4.5 5 Column & Boom with single SAW welding head to the Tennessee-based client.

"Before, our manual fitting was quite accurate, but it was also quite slow. We needed to improve the speed and accuracy of the fit-up of large cylinders with automated solutions, which enable a faster and more efficient process. By using the side support arms, we are now able to support the cylinder as we fit the joint and also throughout the welding process — no more manual fit-ups," said Sciotto.

Custom Steel Fabricators, Inc. is working on a "thick alloy 2205 duplex stainless fabrication project 156" in diameter, where PEMA solutions are already put to use.

Pemamek Ltd, founded in 1970, is a global welding and production automation leader. With the extensive 50-year experience in welding and production automation, Pemamek is dedicated to helping heavy fabrication industries, such as shipbuilding, wind energy, and power generation industry, to raise the level of productivity.

MORE INFO www.pemamek.com

Ipsen continues service, calibrations, support despite virus

The Ipsen service team is committed to supporting customers during the COVID-19 pandemic with both on-site and remote assistance to keep critical heat-treating equipment operational.

Ipsen continues to provide advanced aftermarket support, including instrument calibrations and temperature uniformity surveys (TUS) that adhere to various industry standards, such as Nadcap, AMS2750E, AMS2769C, and MedAccred. Ipsen provides calibration and TUS services for the aerospace and defense, medical device, automotive, and energy industries to help ensure their equipment remains in compliance.

The Ipsen customer service team is the largest in the industry, with regional service managers and field service engineers able to provide immediate local support. Ipsen's trained and experienced technicians provide an extensive range of services, including installation or relocation of equipment, start-up and testing, furnace evaluations and repair, refurbishments, computer and controls upgrades, spare parts, training, and technical support.

In accordance with government requirements, Ipsen is following all necessary safety protocols, including wearing personal protective equipment, maintaining social distancing, limiting face-to-face contact, and increasing the use of remote assistance where possible.

MORE INFO www.ipsenusa.com

Can-Eng Furnaces awarded contract by Metex Heat Treating

Metex's new Can-Eng system will be commissioned for the hardening and tempering of high-volume automotive critical fasteners, stampings, and assembly components. (Courtesy: Can-Eng)

Metex Heat Treating Limited of Brampton, Ontario, has contracted Can-Eng Furnaces International Limited to design and commission a 6,600 lb/hr continuous mesh belt atmosphere furnace system.

This new system will be commissioned for the hardening and tempering of high-volume automotive critical fasteners, stampings, and assembly components. The system includes a computerized loading system, mesh belt-controlled atmosphere hardening furnace, oil quench system, mesh belt tempering furnace, pre- and post-wash systems, and Can-Eng's PET™ System.

By integrating Can-Eng's PET System, Metex has access to vital tracking of its products' status, detailed process data for continuous process improvements, comprehensive equipment diagnostics, cost analysis, inventory management, supervisory control and data acquisition (SCADA) enhanced features to support compliance with CQI-9 guidelines. This recent furnace design integrates enhancements to the radiant heating system that provides Metex with added capacity within a fixed system footprint.

This contract will represent Metex Heat Treating's sixth Can-Eng Furnace System, providing Metex with more than 400,000 lbs./day of continuous atmosphere processing capacity in addition to batch and Induction services, which are provided to customers across Canada and the United States. Metex selected Can-Eng to provide this additional equipment capacity as a result of the continuous improvements integrated into their systems, allowing them to meet the ever-increasing demands of the automotive industry.

Can-Eng Furnaces International Ltd. is an ISO 9001:2015 certified company with its head office and manufacturing facility located in Niagara Falls, Ontario, Canada.

MORE INFO www.can-eng.com

ECHT 2021 and QDE conference issues call for papers

The Quenching and Distortion Engineering conference series follows up on the former series of IDE, organized by IWT Bremen, Germany, and QDE, organized by IFHTSE. These two have been merged into the QDE series. In 2021, the QDE conference is also part of the European Conference on Heat Treatment series, which is supported by European organizations. The conference is scheduled for April 26 – 28, 2021 in Berlin.

An abstract of 300 words maximum should be submitted electronically before acceptance, preferably in Word or as PDF file to papers@echt-qde-2021.de. The deadline for submissions is September 30, 2020. The abstract should include the title of the paper, the authors' names and addresses, telephone and fax numbers, and e-mail addresses. If possible, the name of the lecturer should be given, too. All presented papers will be published in the Conference Proceedings. Selected papers will undergo a review process in order to publish them in a special Issue of *HTM Journal of Heat*

Treatment and Materials and Materials Science & Engineering Technology. Only English language will be used for all abstracts, papers, and presentations.

The ECHT and QDE conference will cover the quenching process as an essential step in the heat treatment of metallic components, and the relation of the distortion potential of a component with all steps of the manufacturing process especially quenching.

The conference addresses the following topics:

- Quenching facilities and controls.
- Quenching media including their characterization, monitoring, and servicing.
- Quenching processes.
- Measurement of distortion and residual stresses in general.
- In-process measurement of deformations, stresses, and phase compositions.
- Control of distortion.
- Quality management aspects.
- Interactions of different production processes.
- Case studies on distortion problems.
- Methods of distortion compensation.
- Modeling of quenching- and distortion-related phenomena (e. g. heat transfer, phase transformation, plasticity, creep, transformation plasticity).
- Determination of boundary conditions (e.g. heat transfer) for process simulation.
- Simulation of individual and subsequent processes such as casting, hot and cold forming, soft and hard machining, and heat treatment, including most prominently quenching.

MORE INFO www.echt-qde-2021.de

Industrial furnace retrofits from Seco/Warwick

In addition to manufacturing new equipment, Seco/Warwick also provides comprehensive repairs and retrofits of already-owned furnaces. (Courtesy: Seco/Warwick)

In addition to manufacturing new equipment, Seco/Warwick also provides comprehensive repairs and retrofits of already-owned furnaces. Old does not necessarily mean unworthy of investing. A leading manufacturer of aviation engine components recently opted for a furnace retrofit.

The scope of the retrofit included a furnace repair along with the replacement of its control cabinet and an upgrade of the atmosphere generators used with the furnace. The scope of furnace repair included, among other things, replacement of its thermal insulation. Thanks to the use of modern and environmentally-friendly materials the device is now better insulated without increasing the original wall insulation thickness. As a result, heat losses through the housing are lower, decreasing process costs.

The principle of Seco/Warwick's Seconomy program is to combine economic drivers with environmentally responsible approaches. Current trends require the reduction and optimization of utilities consumption which guarantee, on the one hand, direct savings in terms of consumer costs, and on the other, reduced impact on the natural environment. This applies both to the energy consumed from the environment and to the pollution discharged post-process.

"Such changes become a reality. There is no economic growth without being conscious about the environment and this also applies to heat treatment. Seco/Warwick is one of the first companies to adapt to the new rules," said Robert Szadkowski, VP business segment aftermarket at Seco/Warwick.

Apart from repairing the furnace, or more accurately upgrading it, there were significant material improvements, including replacing the control cabinet. A modern communication HMI increases safety and enables the operator to intuitively control all functions of the furnace, while adding parallel remote control, monitoring, and reporting capabilities. In addition, the atmosphere generator alongside the furnace received elements that enable it to automatically adjust the volume of generated gas to current needs, optimizing the costs of the entire process. The scope was not determined by chance; a knowledgeable customer and a professional provider combined their efforts to achieve better performance and reliability for lower costs.

"Seco/Warwick determines an individual selection of services for the customer — and this partner is no exception. Repairs are implemented according to the Seconomy assumptions," Szadkowski said. "First, we perform a comprehensive analysis of the device's operation, including its environment, and then we focus on the areas where we can potentially reduce losses and decrease production costs. In this case, the scope covered the furnace itself as well as the independent generators providing the protective atmosphere for the heat-treatment process. Second, we enhance our offering with state-of-the-art control systems that enable safe and easy furnace operation supported with advanced data visualization, reporting, and archiving tools. With our additional remote maintenance supervision option, we increase the safety of production continuity and minimize downtime. Third, with the reduction of utilities consumption and gases discharged to the atmosphere post-process, we limit the impact of the operating device on the natural environment. Our customers can proudly boast environmentally-friendly equipment. Fourth, the safety of the operating personnel is increased. Implementation of non-carcinogenic materials by Seco/Warwick complies with the latest OHS requirements, while releasing the customer from restrictions imposed by the legislation on carcinogenic substances."

Not so long ago, at the beginning of the 21st century, industrial furnaces were commonly manufactured using refractory ceramic fibers (RCF), which modern legislation determined to be harmful. After a retrofit performed by Seco/Warwick, every material used will hold a valid material safety data sheet (MSDS) which details handling of the particular materials as well as the personal protective equipment. Modern materials also have another economic dimension: increased maximum limit of long-term use of the device and its resistance to thermal cycles. This translates to lower total cost of ownership as well as savings on waste disposal.

MORE INFO www.secowarwick.com

Gasbarre upgrades brazing furnace for CQI-9 production

Gasbarre Thermal Processing Systems recently rebuilt and shipped a 24-inch, four zone continuous mesh-belt brazing furnace for an automotive parts supplier in Mexico.

The rebuild included a new 330 stainless steel muffle, new silicon carbide heating elements, new cooling sections, and new furnace controls to meet CQI-9 requirements. The CQI-9 controls package includes data acquisition, preventative maintenance alerts, remote connectivity, furnace parameter trending, and temperature deviation alarms. Gasbarre was chosen as a partner for its brazing expertise, unique controls package, and ongoing service and support of the customer in Mexico.

With locations in Plymouth, Michigan; Cranston, Rhode Island; and St. Marys, Pennsylvania, Gasbarre Thermal Processing Systems has been designing, manufacturing, and servicing a full line of industrial thermal processing equipment for nearly 50 years. Gasbarre's product offering includes batch and continuous thermal processing equipment for both atmosphere and vacuum applications as well as a full line of alloy fabrications, replacement parts, and auxiliary equipment, which consists of atmosphere generators, quench tanks, washers, and charge cars. Gasbarre's equipment is designed for the customer's process by experienced engineers and metallurgists.

MORE INFO www.gasbarre.com

Solar Atmospheres of Western PA is constructing a 15,000-square-foot building to make room for the new VOQ furnace line. (Courtesy: Solar Atmospheres)

Solar Manufacturing, Solar Atmospheres team on VOQ furnace

Solar Atmospheres of Western PA (SAWPA) understands the need to expand its material hardening repertoire by adding oil quenching capabilities. The question has been how to make this process safer and greener? The explosiveness of the protective endothermic gas along with the flammability of open oil quench tanks has provided concerns with regard to environmental, health, and safety standards established by the SHARP recognition program. In 2019, Solar Manufacturing and Solar Atmospheres commenced engineering meetings with the goal to design and build a U.S.-manufactured, safe, and quality vacuum oil quench furnace.

A new Solar 36" x 36" x 48" vacuum oil quench (VOQ) furnace, capable of safely quenching 2,000-pound loads without carbon potential concerns, will be operational in early 2021 at SAWPA.

SAWPA is currently constructing a 15,000-square-foot building to make room for this VOQ furnace line. Besides the Solar VOQ furnace, the additional equipment includes a parts washer, two tempering furnaces, and a charge car. The interconnecting 30 foot-tall-building will be completed in mid-summer 2020, making the entire SAWPA complex 120,000 square feet under one roof.

MORE INFO www.solaratm.com

Shougang places another major order with Tenova

In December 2019, the Chinese company Shougang Qian'an Electrical Vehicle Steel Co., Ltd. signed another major order with Tenova LOI Thermprocess, a global company in the field of heat-treatment plants based in Germany. The order includes the heat-treatment portion (furnace system) for two annealing and coating lines (ACL) for non-grain-oriented (NGO) electrical strip.

The two furnace systems, for which the basic design is almost complete, bear the internal designation SACL 7 & 8 and will meet the highest requirements for the production of non-grain-oriented electrical steel. As is well known, they are at the core of every treatment line for electrical steel with a special and exact temperature control, changing gas compositions, a precisely working slow and fast cooling system as well

Two of seven previously delivered heat-treatment plants for electrical steel to Shougang. (Courtesy: Tenova LOI Thermprocess)

as an automated working method that is as model-based as possible.

The scope of the contract includes engineering, the largely turnkey delivery of all furnace-related key components, as well as supervision of assembly and commissioning including training. In addition to the electrical equipment belonging to the furnaces, the control components as well as the associated software and a mathematical furnace management model are also supplied. Local provision and support are provided by Tenova Technologies Tianjin Co. Ltd., Tenova's subsidiary in China.

The large number of references for comparable systems, the short implementation time, and the proven mathematical model were important factors that led Shougang to choose LOI-technology. Shougang has been successfully operating seven modern lines for the heat treatment of electrical steel (GO) for years, where the heat-treatment part has always been supplied by Tenova LOI (2x APL, 3x DCL, 2x FCL und 3x MBAF).

In the period 2000-2020, Tenova has received 61 orders for heat-treatment systems for electrical steel. Thirty-five plants are completely new plants. In the past 10 years, LOI Thermprocess has been selected seven times as a supplier for annealing and coating systems for the heat treatment of dynamo strip. This means that Tenova LOI has a market share of almost 100 percent for new systems of this type.

Shougang Qian'an Electrical Vehicle Steel Co., Ltd. is a subsidiary of the Chinese company Shougang Iron & Steel based in Beijing, China. It is one of the major steel companies in China and one of the three largest electrical sheet producers in the country.

MORE INFO www.tenova.com

Kuczma heat treater picks Seco/Warwick vacuum furnace

A top-tier Vector® vacuum furnace equipped with gas quenching from Seco/Warwick will be used by a commercial heat-treating plant. This time, the Kuczma commercial heat treatment chose this state-of-the-art single-chamber vacuum furnace.

Vector is the most popular vacuum technology for heat treatment selected by commercial plants worldwide. This vacuum furnace is a very efficient and versatile system used for heat treating many types of materials and metal alloys. Its functionality includes gas hardening and tempering, annealing, brazing, and degassing. This Vector model — a vacuum furnace equipped with 1.5 bar gas quenching pressure — will significantly increase the capacity of the Kuczma Hardening Plant and will enable it to process parts with dimensions up to 600 x 600 x 900 mm.

This will be the first Seco/Warwick furnace operated by the Kuczma Hardening Plant. Commercial heat treaters around the world select Seco/Warwick technologies for many reasons, most importantly for their versatility, reliability and precision.

"The Vector technology is one of the two most sought-after solutions from Seco/Warwick for heat treatment by hardening plants worldwide. CaseMaster Evolution (CMe) is a multi-chamber vacuum furnace with oil or gas quench. Both solutions share their process versatility and operating flexibility that distinguish the Seco/Warwick solutions" said Maciej Korecki, vice president, vacuum business segment, Seco/Warwick.

"Kuczma Hardening Plant specializes mostly in vacuum quenching in gas, oil, and gas nitriding of injection mould components and dies. The company has many years of experience and aims to provide services of the highest quality with the shortest lead times possible," said Jerzy Kuczma, Kuczma Hardening Plant owner, "These are denominators we share with our technology partner, whom I have known personally ever since Elterma. Standards have neither changed for Seco/Warwick nor for Kuczma Hardening Plant. We set the requirements high both for us and our selected technologies. Vector clearly meets them. On one hand, the Seco/Warwick furnace will enable us to process larger components and increase our output for smaller ones, on the other, it will enable directional cooling sideways or top/bottom."

The key features of the furnace for Kuczma commercial hardening plant include large working space in the furnace chamber — 600 x 600 x 900 mm — that accommodates items of larger dimensions, increases output, and ensures versatility in processing a wide range of steels. A particular, tailor-made solution implemented in this furnace consists of the directional cooling, which enables quenching from sides as well as top and bottom.

The Vector furnace for this project features the unique sideways cooling that makes it possible to optimally adjust the gas cooling system to the batch configuration. Nowadays, customers from various industries expect increasing reliability, performance, and better results of heat treatment. Seco/Warwick Group's Vector® vacuum furnace model responds to these expectations.

MORE INFO www.secowarwick.com

IHEA MEMBER PROFILE

Honeywell Thermal Solutions offers a range of thermal solution technologies

Honeywell has an extensive history in combustion processes and controls, including solutions for industrial combustion industries. Honeywell Thermal Solutions united the combustion industry's leading brands to provide an extensive range of thermal solutions globally: Honeywell Combustion Controls, Honeywell Combustion Safety, Honeywell Combustion Service, Eclipse, Exothermics, Hauck, Kromschröder, and Maxon.

Honeywell has created a comprehensive portfolio of thermal solution technologies, software as a service (SaaS), and outcome-based service offerings. Continued innovation is driving Honeywell Thermal Solutions leadership position as a collaborative partner for customers wanting to drive better business outcomes with leading edge thermal processes.

With more than 100 years of industry-leading experience, Honeywell Thermal Solutions provides a combination of expertise and solutions that include:

› **Burners:** For low- and high-temperature industrial processes.

› **Burner management systems (BMS):** Single and multi-burner controllers, UV, infrared, visible and combination flame detectors, air fuel rationed O2 trim systems, and application-specific programmable BMS controllers.

› **Fuel delivery systems:** Pressure regulation, shut-off valves, control valves, and fuel-air ratio systems for heavy industrial process applications.

› **Engineered-to-order solutions:** Delivering the most compliant turnkey systems to code and standards with the greatest depth of technical know-how.

› **Connected solutions:** Honeywell Thermal IQ, developed by thermal-process experts, is the remote monitoring solution that securely connects your combustion equipment to the cloud, making critical thermal-process data available anytime, anywhere, on any smart device or desktop.

› **Remote Expert Support with Virtual Combustion Technician:** This software allows clients and certified Honeywell technicians to collaborate and solve problems via a smart phone app. VCT provides a safe and reliable way for clients to troubleshoot problems with a thermal domain expert virtually looking over their shoulders.

Whether it is high-temperature and low-temperature industrial burners or burner management systems for industrial process applications, Honeywell Thermal Solutions has a portfolio that covers every need. This portfolio of thermal transfer solutions covers everything from commercial to heavy-industrial sectors and includes:

› End-to-end customer experience (from opportunity, to delivery, to start-up, to operation, to post-shipment).

› Global service teams providing standard service contracts, troubleshooting, burner tuning for efficiency, emissions, and burner performance.

› Turnkey solutions for new and existing applications.

Honeywell Thermal Solutions maximizes the connectivity of real-time and cyber-secure operating data in thermal processes and automates predictive analytics to provide outcome-based, predictive maintenance to bring significant benefits to the operation.

› Remote monitoring software applications, data analytics, and outcome-based projects.

› Executing projects from start to finish, with multiple solutions from simple to complex.

In a highly competitive global marketplace, industrial organizations increasingly seek digital intelligence to manage and operate hundreds of assets from a single site or across an enterprise and address critical operating demands. They need effective tools to transform process data into real-time information regarding process performance, equipment health, energy consumption, and emissions monitoring. Honeywell Thermal Solutions maximizes the connectivity of real-time and cyber-secure operating data in thermal processes and automates predictive analytics to provide outcome-based, predictive maintenance to bring significant benefits to the operation. These benefits include increased visibility and accountability, minimized unplanned downtime and maximum uptime, increased efficiency, and enhanced safety.

Honeywell Thermal Solutions will continue to address key industry trends as a global industrial thermal solutions provider with leading technology, software and cloud-based, connected strategies.

MORE INFO www.thermalsolutions.honeywell.com

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

Various alloying elements are used to form aluminum alloys. Understanding the element types is key to choosing and adding the right ones to get the desired results.

The heat treatment of aluminum – Introduction

Aluminum's many desirable properties, such as high strength-to-weight ratio, good corrosion resistance, ease of processing, and low cost, make it a very widely used material in many applications. Because of this wide use, designers are often challenged with selecting the "best choice" from numerous alloys and several heat-treating processing options available. The proper heat treatment of these alloys is necessary to achieve the specified properties and performance.

Aluminum in many forms has been used in aircraft since the early beginning. This is because aluminum alloys can be heat-treated to relatively high strengths, while maintaining low weight. It is easy to bend and machine, and cost of material is low. Because of these advantages, it is the most common material used in aerospace today. It is used in the manufacture of advanced commercial aircraft such as the Boeing 777, Airbus 380, and military aircraft such as the Boeing UCAV or the Boeing F/A-18 E/F.

When used in conjunction with aluminum alloys, the term 'heat treating' is generally restricted to solution heat treatment, quenching, and subsequent aging of aluminum alloys to increase strength and hardness. These usually are referred to as the 'heat-treatable' alloys to distinguish them from those alloys in which no significant strengthening can be achieved by heating and cooling. The latter, generally referred to as 'non-heat-treatable' alloys, depend primarily on cold work to increase strength.

In this short article, we will describe the various alloying elements that form the different aluminum alloys and classify them according to types of aluminum alloys.

ALLOYING ELEMENTS

Generally, cast and wrought aluminum alloys are classified either as heat-treatable (precipitation hardenable) alloys or as solid-solution alloys, as summarized in Figure 1. Wrought and casting alloys also are further designated by temper codes to indicate condition and the prevalent strengthening mechanism briefly as follows:

- Non-age-hardening alloys are solid solution strengthened and are indicated by an as-fabricated temper (F) or annealed temper (O).
- Wrought solid-solution alloys may be further strengthened by work-hardening (H-tempers).
- Age-hardening alloys are precipitation strengthened indicated by heat-treatment tempers (T-tempers).
- Depending on the alloying elements, strengthening of aluminum can be achieved by heat treatment or by solid solution strengthening (often in conjunction with work hardening). The elements most commonly present in commercial aluminum alloys for strengthening are copper, magnesium, manganese, silicon, and zinc. Minor alloying elements, which are added for special properties or metallurgical effects, include: Fe, Li, Ti, B, Zr, Cr, V, Sc, Ni, Sn, and Bi. In addition, silicon, which has a eutectic reaction (at 577°C with 12.6 wt% Si) and is added to improve the fluidity during casting and is thus an alloying constituent in casting alloys.

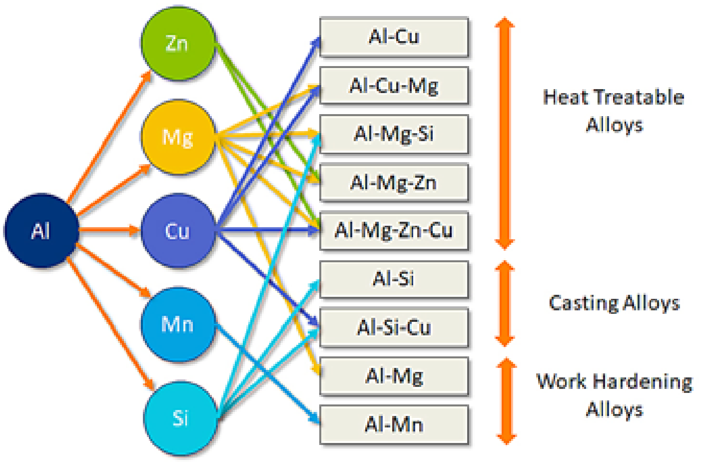


Figure 1: Alloying elements used in aluminum alloys, classified to alloy type [1].

Elements and combinations that form predominantly second-phase constituents with relatively low solid solubility include iron, nickel, titanium, manganese, and chromium, and combinations thereof. Manganese and chromium are included in the group of elements that form predominantly second phase constituents.

Copper is one of the most important alloying ingredients for aluminum, because of its appreciable solubility and its strengthening effect from precipitation hardening. The binary Al-Cu system is the classic example of precipitation hardening, and the age hardening of binary aluminum-copper alloys is one of the most studied systems.

Most commercial Al-Cu alloys contain other alloying elements. Aluminum-copper alloys containing 2 to 10 percent Cu, generally with other additions, form important families of alloys. The aluminum-copper system is the basis for the wrought 2xxx and cast 2xx.x alloys, and many other heat-treatable alloys contain copper. Most contain other alloying elements such as magnesium.

The main benefit to adding magnesium to aluminum-copper alloys is the increased strength possible following solution heat-treatment and quenching. In both casting and wrought alloys, as little as 0.05 percent magnesium is effective in changing aging characteristics.

The Al-Mg system is the basis for the wrought 5xxx and cast 5xx.x non-heat-treatable aluminum alloys. The addition of magnesium provides solid solution strengthening without unduly decreasing the ductility. The Al-Mg alloys offer an excellent combination of solid-solution strengthening, corrosion resistance, and the strengthening of wrought alloys by work hardening.

Silicon is a ubiquitous impurity in commercial aluminum alloys.

The aluminum-zinc alloys have been known for many years, but hot cracking of the casting alloys and the susceptibility to stress-corrosion cracking of the wrought alloys curtailed their use. However, the addition of copper and/or magnesium with zinc results in attractive compositions for heat treating or natural aging.

Impurity levels in electrolytic commercial aluminum in the range of 0.01 to 0.15 wt% Si, and the presence of iron greatly reduces the solubility of silicon in aluminum.

As an alloying element, the outstanding effect of silicon additions to aluminum and its alloys is the improvement in casting characteristics. Aluminum-silicon alloys that do not contain copper additions are used when good castability and good corrosion resistance are needed.

Aluminum-copper-silicon alloys are the most widely used aluminum casting alloys. The amounts of both additions vary widely, so that the copper predominates in some alloys and the silicon in others. In these alloys, the copper contributes to strength, and the silicon improves castability and reduces hot shortness. Aluminum-copper-silicon alloys with more than 3 to 4 percent Cu are heat treatable, but usually heat treatment is used only with those alloys that also contain magnesium, which enhances their response to heat treatment.

The Al-Mg-Si system also is the basis for the heat-treatable 6xxx series of heat-treatable wrought alloys. The wrought Al-Mg-Si (6xxx) alloys contain up to 1.5 percent each of magnesium and silicon in the approximate ratio to form Mg_2Si, that is, 1.73:1.

The aluminum-zinc alloys have been known for many years, but hot cracking of the casting alloys and the susceptibility to stress-corrosion cracking of the wrought alloys curtailed their use. Zinc confers little solid solution strengthening or work hardening to aluminum, and no significant technical benefits are obtained by the addition of just zinc to aluminum. However, the addition of copper and/or magnesium with zinc results in attractive compositions for heat treating or natural aging. Usually, other elements, such as chromium, are also added in small quantities.

The addition of magnesium to the aluminum-zinc alloys develops the strength potential of this alloy system, especially in the range of 3 to 7.5 percent Zn. Magnesium and zinc form $MgZn_2$, which produces a far greater response to heat treatment than occurs in the binary aluminum-zinc system. The Al-Zn-Mg precipitates provide the basis for the 7xxx wrought alloys and the 7xx.x cast alloys.

The addition of copper to the Al-Zn-Mg alloys results in the highest-strength aluminum-base alloys commercially available. In this alloy system, zinc and magnesium control the aging process. The effect of copper is to increase the aging rate. Copper also increases quench sensitivity upon heat treatment. In general, copper reduces the resistance to general corrosion of Al-Zn-Mg alloys but increases the resistance to stress corrosion.

Lithium reduces the density and increases the modulus of aluminum alloys. In binary alloys it forms metastable Al_3Li precipitates and combines with aluminum and copper in Al-Cu-Li alloys to form many Al-Cu-Li phases. Because of its high cost relative to other alloying elements, lithium alloys have been found to be cost effective thus far only in space and military applications. Some applications in sporting equipment such as bicycle frames or baseball bats have also been used.

Titanium (Ti) is used primarily as a grain refiner of aluminum alloy castings and ingots. The grain-refining effect is enhanced with boron. Titanium depresses the electrical conductivity of aluminum, but its level can be reduced by the addition of boron, which forms insoluble TiB_2.

Zirconium (Zr) additions in the range of 0.1 to 0.3 percent are used to form a fine precipitate of intermetallic particles that inhibit recovery and recrystallization. Most 7xxx and some 6xxx and 5xxx alloys developed since the 1960s contain small amounts of zirconium, usually less than 0.15 percent, to form Al_3Zr dispersoids for recrystallization control.

An increasing number of alloys, particularly in the Al-Zn-Mg family, use zirconium additions to increase the recrystallization temperature and to control the grain structure in wrought products. Zirconium additions leave this family of alloys less quench sensitive than similar chromium additions.

Zirconium additions have been used to reduce the as-cast grain size, but its effect is less than that of titanium. In addition, zirconium tends to reduce the grain refining effect of titanium plus boron additions, so that it is necessary to use more titanium and boron to grain refine zirconium-containing alloys.

CONCLUSION

In this short article, we have discussed the various alloying elements that are used in aluminum alloys and described why they are added. In the next articles we will dive deeper into the heat treatment of aluminum and describe some of the problems and solutions to those problems.

As always, should you have any comments regarding this article, or suggestions for other articles, please contact the editor or author.

REFERENCES

[1] R. Davis, Aluminum and Aluminum Alloys, vol. ASM Specialty Handbook, Metals Park, OH: ASM International, 1993.

ABOUT THE AUTHOR

D. Scott MacKenzie, Ph.D., FASM, is senior research scientist-metallurgy at Quaker Houghton Inc. For more information, go to https://home.quakerhoughton.com/

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

When faced with specification changes, it's a quality representative's duty to adapt processes to comply with the revisions.

Gap analysis can guide procedure changes

Well-designed procedures are crucial to any business operation, whether it's a simple task of following a procedure to construct a cardboard box, or something more complex such as checking an airplane for safety prior to takeoff. It's a step-by-step process that guides the person performing the task with written instructions. Its objective is to maintain compliance while minimizing variation, so your company can consistently produce repeatability and desired results for any process that is used either frequently or infrequently. A procedure should be detailed as such that it meets specification and/or standard requirements, yet simple enough that any employee can read through it, follow its instructions to the letter, and achieve the same results.

Some would argue that aligning your company's procedures in conjunction with specification requirements is easier said than done. Why? Certain areas of your procedures are designed to meet those requirements depending on what sector your business serves, but a major or even slight change will alter how your procedures are written and implemented. Speaking from my own experience, evolving changes had a dizzying effect when locating new requirements and implementing them into our existing procedures. This month's column will focus on how a gap analysis approach can support the end goal of meeting revision changes, and at the same time minimize the pain of locating and executing those new requirements.

Almost every person in quality knows this situation quite well. A revision or superseding document has been released, and your company uses that document to process and certify jobs. It's your duty as a quality representative to adapt your processes to the new document. In order to do that you must revise your procedure's written instructions on how to meet those new requirements. How do you account for all the changes made and align your procedures to meet them?

SPECIFICATION CHARACTERISTIC ACCOUNTABILITY

SPECIFICATION: **NAME OF SPECIFICATION** Revision: **LEVEL OF REVISION**

Char. #	Requirement Clause by Clause Language	Zone CLAUSE #	WHERE ACCOUNTED IN YOUR PROCEDURE	Meets Req't Y/N	If NO, CA steps taken.	Meets Req't after CA Y/N
1		1.1	Example: 2.2.1	Y		
2		1.2	Example: 3.0	Y		
3		1.3				
4		1.4				
5		1.5				
6		1.6				
7		1.7				
8		2.0				
9		2.1				
10		2.2				
11		2.3				
12						

A specification accountability sheet does exactly what its name indicates. It forces you to determine whether your procedures are accountable to a specification.

A system that was introduced to me by one of my mentors, and something I consider to be very effective, is to apply a gap analysis approach. For those of you who are new to this definition or are new to quality in general, gap analysis is a method that measures desired results versus actual results. If your company fails to meet desired results, then there is a gap between desired versus actual. To make applicable to this topic, gap analysis will analyze your existing procedures and find gaps when comparing it to new requirements. The type of gap analysis I use has been called numerous things, but I like to call it a specification accountability sheet.

A specification accountability sheet does exactly what its name indicates. It forces you to determine whether your procedures are accountable to a specification. It takes a clause by clause method when determining if your procedures meet the new changes in a document. If your procedure is lacking or not accounting for a new requirement, the sheet will not only show you where your gap lies, but also give you space to make notes and decide on corrective action. The same thing applies when your procedure accounts for new requirements. The sheet will ask you where this clause is accounted for and how it meets the requirement. This method can be monotonous to some, but I find that this is a great tool to dig deep into a revision, provide clear answers on your procedures, and locate where changes need to be made. From my experience when using this method, there are no clauses unidentified, therefore you don't need to worry about whether you were thorough enough when seeking accountability.

After you've accounted for new requirements and made changes to your procedure, it's time to implement those changes to your staff through training. This is perhaps the easiest thing to do after you've spent a considerable amount of time assessing your company's procedural accountability. It's also a great opportunity to refresh your staff on the procedure in general. A simple yet straight-to-the-point approach would be to outline each new change and use your own training system to focus on them. There are many ways to do this, so stick with what works best for your company.

Revisions to process specifications are inevitable in the heat-treating industry. New technology or new studies can make discoveries that allow processes to become more efficient, more precise, and achieve superior quality. Although it can be painful to adapt your procedures to these constant changes, being prepared and having a system in place to identify those changes can make the work much easier.

At this point, you should have a good idea on how specification accountability can strengthen your capacity to find gaps within your procedures. It's a system that requires diligence and persistence from the personnel performing this task, but I can assure you that it will give you peace of mind knowing that you've accounted for every change made.

ABOUT THE AUTHOR

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

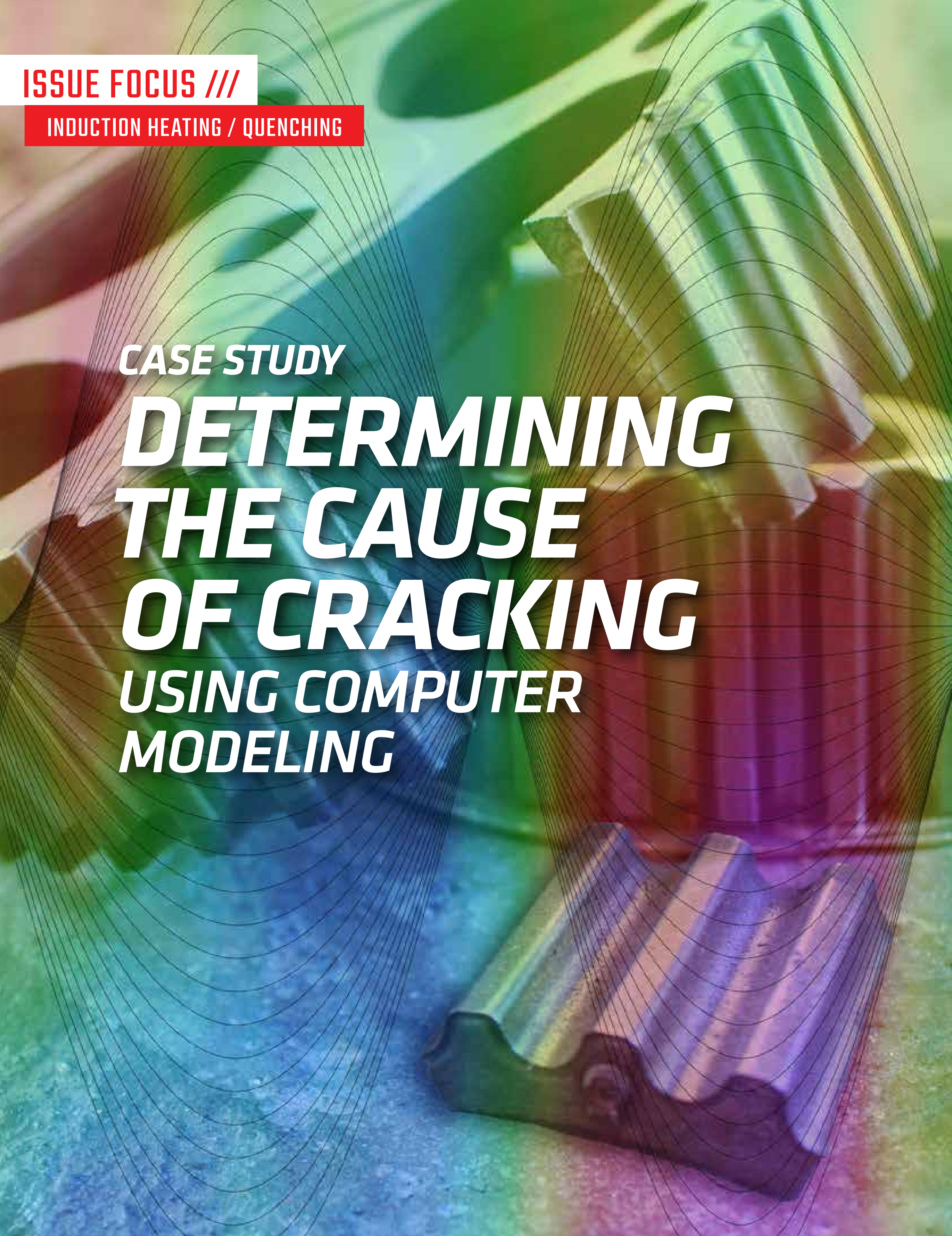
ISSUE FOCUS ///

INDUCTION HEATING / QUENCHING

CASE STUDY

DETERMINING THE CAUSE OF CRACKING

USING COMPUTER MODELING



Heat-treatment simulation software can be a powerful tool in root cause failure analysis of induction-hardened parts.

By JUSTIN SIMS and CHARLIE LI

During an induction-hardening process, the part surface is heated using a medium- to high-frequency inductor. Once the desired depth of austenitization is reached, the part surface is quenched to transform the austenite to martensite. Compared to traditional furnace heating and liquid quenching, the induction process is much more energy efficient due to the rapid heating and formation of only a layer of austenite on the surface as opposed to austenitizing the entire volume of the part. The induction process also gives more options for process improvements with respect to case profile and residual stresses due to the large temperature gradient that exists between the surface and the core of the component. [1-3] Material volume expansion occurs with the transformation from austenite to martensite, and this induces compressive surface stresses. However, stress evolution during a hardening process is nonlinear and part geometry can play a significant role in the stresses formed.

Phase transformations also cause changes in the thermal and mechanical properties of the steel, the volume of the material, the internal stresses between different phases, and internal stresses within the same phase. Simulation of the heat-treating process is complex, requiring complex algorithms and accurate databases of thermal, mechanical, and metallurgical properties of all phases over a large range of temperatures. Several commercial codes are available for heat-treatment modeling, but DANTE was used for the following case study. DANTE is a multi-phase material model that links to the finite element packages ABAQUS or ANSYS. DANTE is used to predict the phases, dimensional change, and in-process and residual stresses in a steel component resulting from a heat-treatment process of a carburized or through-hardened component. [4-5] The diffusive and martensitic phase transformation modes resident in DANTE are described in general by Equations 1 and 2:

$$\frac{d\Phi_d}{dt} = \nu_d(T)\Phi_d^{\alpha 1}(1-\Phi_d)^{\beta 1}\Phi_a \qquad \text{Equation 1}$$

$$\frac{d\Phi_m}{dT} = \nu_m(1-\Phi_m)^{\alpha 2}(\Phi_m+\varphi\Phi_d)^{\beta 2}\Phi_a \qquad \text{Equation 2}$$

where Φ_d and Φ_m are the volume fractions of individual diffusive phases and martensite transformed from austenite, respectively; Φ_a is the volume fraction of austenite remaining to transform; ν_d and ν_m are the respective mobilities of transformation, and ν_d is a function of temperature and ν_m is a constant; $\alpha 1$ and $\beta 1$ are material-related constants of diffusive transformation; and $\alpha 2$, $\beta 2$, and φ are constants of martensitic transformation. For each individual metallurgical phase, one set of transformation kinetics parameters is required.

Figure 1 is a strain plot for a dilatometry sample generated from the DANTE material database for AISI 4130 (the steel alloy used for the case study); the horizontal axis is temperature, and the vertical axis is strain. Starting from room temperature, the sample is heated and cooled at a rate of 25°C/s, which is the approximate rates for the component in this case study. DANTE uses rate-based kinetics for both heating and cooling. Rate-based heating kinetics are important for induction hardening processes since the heating rates are generally far from an equilibrium condition. Figure 2 shows a time-temperature-transformation diagram for AISI 4130, using the nominal alloy chemistry generated from the DANTE material database. The DANTE software is also capable of modifying the hardenability of the steel based on slight modifications to the alloy chemistry. This case study used the nominal alloy chemistry for AISI 4130.

DANTE has a standard material database that includes all the necessary parameters needed to execute a heat-treatment simulation for many low- and medium-alloy steels. However, DANTE does not model the electromagnetic phenomenon of induction heating. Instead, DANTE can either map in the Joule heating history predicted by an electromagnetic software, or the Joule heating history can be determined from the component case depth. In this case, the Joule heating history was determined from the component case depth at critical locations.

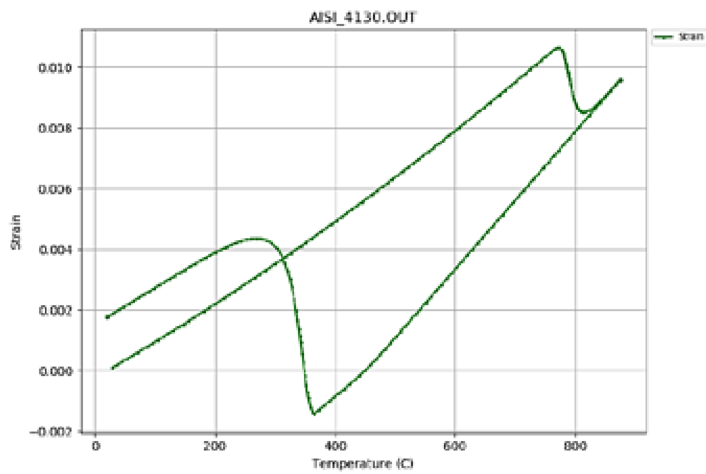


Figure 1: Dilatometry curve from the DANTE material database for AISI 4130 heated and cooled at 25° C/s.

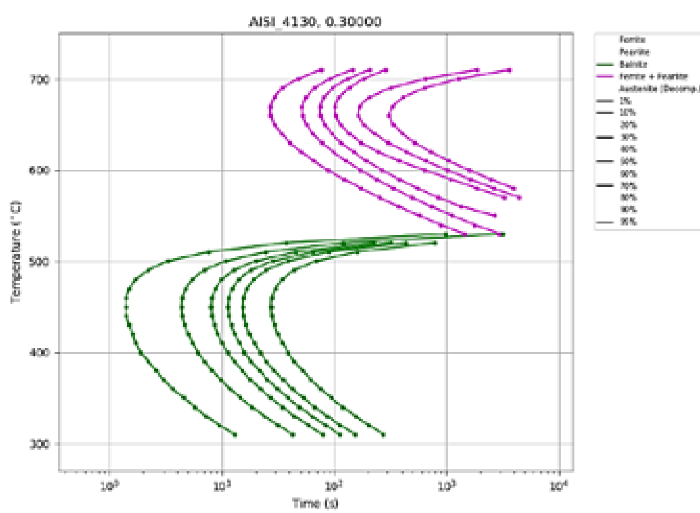


Figure 2: TTT plot for AISI 4130 from the DANTE material database.

Figure 3: AISI 4130 steel coupler examined in this case study.

Figure 4: Inductor and quench unit used to harden the coupler.

COMPONENT, PROCESS, AND MODEL

A large steel coupler made of AISI 4130, shown in Figure 3, was induction hardened using a scanning induction process. The component has a non-axisymmetric bore dimension of approximately 500 mm, an outer diameter of approximately 800 mm, and a height of approximately 500 mm. The inductor and quench head are shown in Figure 4. The inductor has a width of 50.8 mm and a travel speed of 1.27 mm/s. The spray exits the bottom of the inductor fixture and contacts the part 12.7 mm below the inductor, leading to a quench delay of 10 seconds. The coupler was experiencing cracking at a fillet in the bore of the component, as shown in Figure 5. The cracking mode suggested that high in-process circumferential stresses were responsible.

To determine the cause of cracking, a three-dimensional finite element analysis using the DANTE heat-treatment simulation software was conducted. The model was constructed and executed in ABAQUS Standard. Figure 6(A) shows the full CAD model, and Figure 6(B) shows the quarter-meshed model used for the finite element analysis. A quarter model can be used due to the symmetry of the part and because the heating and cooling conditions are assumed to act uniformly over all surfaces of the part in the circumferential direction. The quarter model consisted of 31,449 linear hexagonal elements and 34,680 nodes, with a higher mesh density near the bore surface to capture the high thermal and stress gradients present in an induction hardening process.

Figure 5: Crack in fillet of coupler.

DISCUSSION

The model predicted a high tensile hoop stress in the location where cracking was witnessed on the actual component. DANTE does not predict the propensity to crack. In this case, the predicted surface tensile stresses are high enough to cause surface cracking of as-quenched martensite in AISI 4130, especially if any surface defect is present. Figure 7 shows a plot of hoop stress as a function of depth from the bore surface at the location of cracking. The inset of Figure 7 shows the hoop stress as a contour plot over the entire component. The local coordinates for the hoop stress line plot are relative to the fillet in the

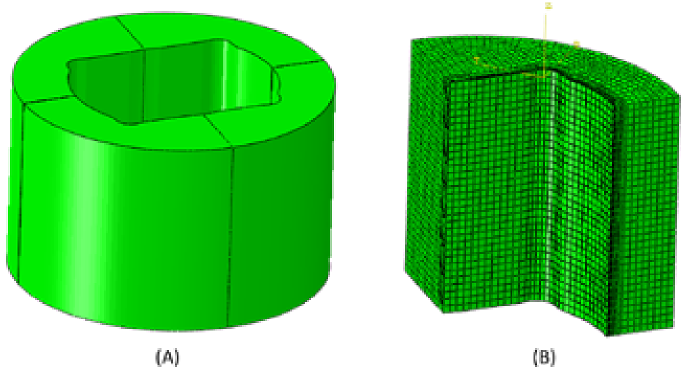


Figure 6: A) Full CAD model of coupler, B) Quarter, finite element model used for case study.

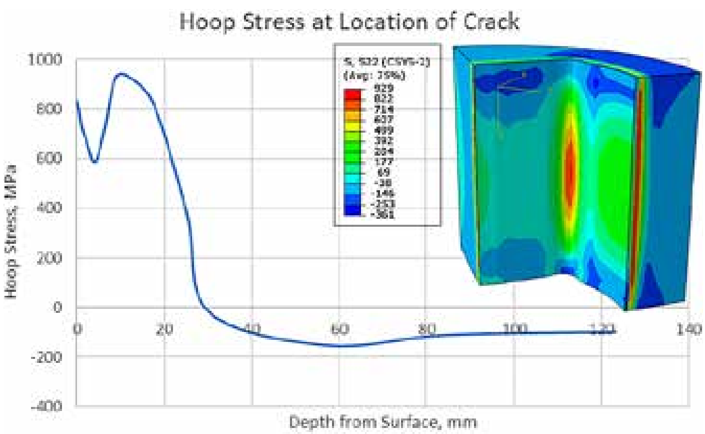


Figure 7: Plot of hoop stress vs. depth at crack location.

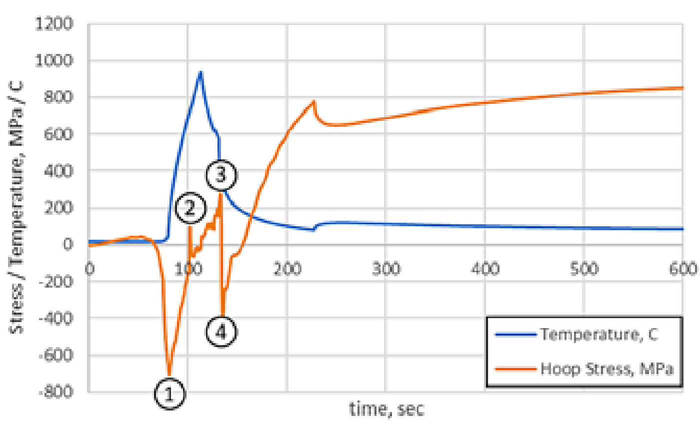


Figure 8: Plot of hoop stress and temperature vs. time at the location of cracking.

bore. The local coordinates for the contour plot are relative to the outer diameter to represent subsurface stresses more accurately.

The high tensile stress under the bore surface is expected and is a consequence of the surface hardening process. Properly surface hardened parts should have a layer of surface compression, followed by a layer of tension. The subsurface tensile stresses are generally in response to the surface compression and are there to balance the compressive stresses. For this case, the induction hardening process resulted in substantial surface tension, even away from the problematic area. This can be quite common for induction hardened parts. As the martensite transformation front proceeds from the bore surface outward, it exerts an outward force on the freshly formed martensite. This behavior can reduce some of the compression created from the martensite volume expansion, even driving the bore surface into tension if the case is deep enough. For carburized components, the transformation starts subsurface in the lower carbon regions and progresses toward the regions of higher carbon. The carburized hardening behavior will always result in surface compressive stresses since the surface is the last volume of material to transform.

The high tensile stress under the bore surface is expected and is a consequence of the surface hardening process. Properly surface hardened parts should have a layer of surface compression, followed by a layer of tension.

Figure 8 shows the time history of temperature and hoop stress at the location of cracking. There are several interesting aspects to this history. The following is a discussion in reference to the four points marked on the plot in Figure 8. Point 1 shows the instant the location begins to be heated by the inductor. Leading up to the time at Point 1, the surface goes into compression to balance the tensile stress generated from the heating of the material just below the location in question. Generally, heating the bore surface drives the surface into compression as the material tries to expand, but is unable to because it is constrained by the surrounding material. However, in this case, heating causes tension. This is due to non-axisymmetric geometry of the part and the fillet being spread open by the expanding material to either side of the fillet and stretching the material in the fillet region.

Point 2 in Figure 8 is the instant the material begins its transformation to austenite. Generally, the shrinkage associated with the transformation causes tensile stresses to be formed. However, in this case, the tension is relieved due to the bore surface shrinkage that allows the fillet to close and the tensile stress to decrease. Up to this point, the behavior related to stress formation has been the opposite of what is normally observed during a hardening process. This is all due to the unique geometry of the bore. By having flat, orthogonal surfaces in the bore and an outer axisymmetric shape, it creates unique stress concentrations in the fillet.

Point 3 in Figure 8 is the moment the surface point begins to transform to martensite. The surface is driven into compression due to the volume expansion of the martensite phase from the austenite phase. This behavior is common during a hardening process, since not even geometry can alter the high compression generated from the austenite-to-martensite transformation.

Point 4 is the end of the martensite transformation, but the bore surface of the part is still cooling. The cooling creates surface tension at the critical location due to the opening of the fillet as the flat surfaces to either side thermally contract. It is this final 200°C (320°F) of cooling that causes the component fillet to crack as the surface tensile stress exceeds 800 MPa (116 ksi). This is in excess of the tensile strength of AISI 4130 in the tempered condition and should also be in excess of the as-quenched tensile strength as well. If it is not in excess outright, any minor surface defect or inclusion will create stress concentrations in excess of the allowable tensile strength.

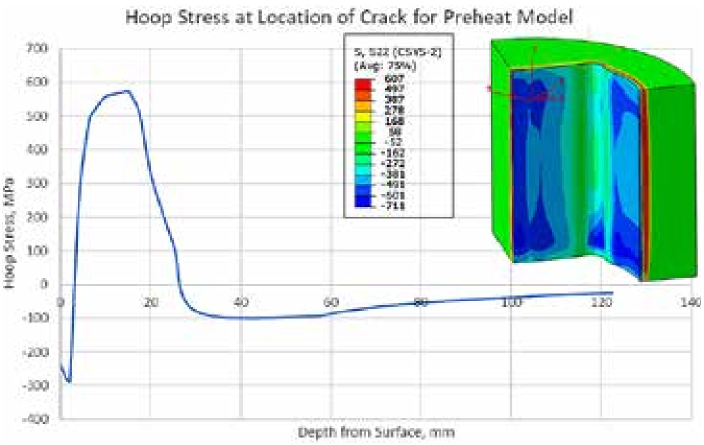


Figure 9: Plot of hoop stress at crack location for a preheated component.

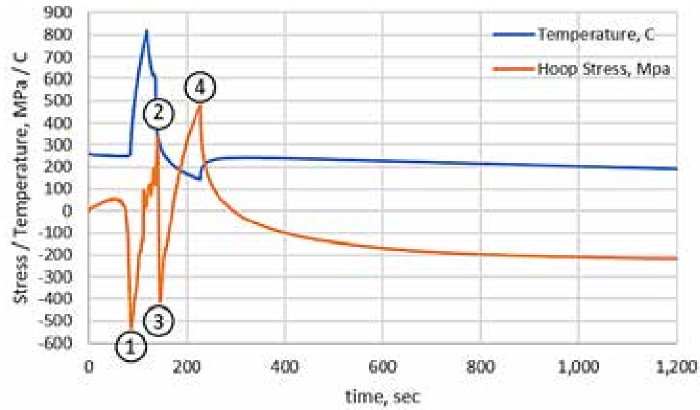


Figure 10: Plot of hoop stress and temperature vs. time at the location of cracking for a preheated component.

PROCESS IMPROVEMENT

With an understanding of the cause of the cracking, a solution could then be sought. The concern was that cooling after the martensite transformation was causing the cracking issues. The easiest way to rectify this type of behavior is to use preheating to raise the temperature of the entire component before induction hardening begins. This can be accomplished using sub-critical furnace heating or a low-frequency induction heating process. By doing so, the entire component will cool and shrink after hardening is complete, pulling the surface into compression.

A single preheating temperature of 260°C (500°F) was modeled to show the feasibility of this concept. Figure 9 shows the residual hoop stress profile in terms of depth at the crack location, with the local coordinates relative to the fillet in the bore. The inset in Figure 9 is a contour plot of the hoop stress over the entire component with the local coordinates relative to the outer diameter. As can be seen, the residual stress is now in compression. However, the complete time history must be examined to ensure there was no cracking propensity prior to the component reaching room temperature. Figure 10 shows the hoop stress as a function of time for a point on the surface at the cracking location. A brief discussion with respect to the four points shown in Figure 10 follows.

As with the non-preheated coupler, the first point goes against normal heating behavior as it is driven into tension by the induction heating process. The compression prior to Point 1 is in response to the material just below it going into tension from the heating process. Point 1 is the instant the area in question begins to be heated by the inductor. The transformation to austenite is not as pronounced as with the non-preheated sample, and Point 2 on Figure 10 shows the instant the martensite transformation begins on the surface at the location of cracking. Point 3 shows the end of the martensite transformation. As with the non-preheated coupler, the surface is pulled into tension as the material cools from the martensite finish temperature. However, upon reaching 200°C (500°F), the stresses begin to reverse as the entire component begins to cool from the preheat temperature. This cooling of the entire body pulls the entire surface into compression, not just the area associated with the cracking. While a preheat temperature of 200°C (500°F) effectively removed the tension on the surface of the component and appears to have reduced the propensity for cracking, the temperature is by no means optimized for this particular component. Further modeling could be used to determine the optimal preheat temperature for compressive residual stress, though the activity was not performed for this particular case. The customer was happy with the results provided by the 200°C (500°F) preheat.

In conclusion, heat-treatment simulation software such as DANTE can be a powerful tool in root cause failure analysis of induction hardened parts. By using DANTE, it was possible to determine the cause of cracking for a large, induction-hardened steel coupler. The cause of cracking was related to the cooling after the transformation to martensite was already complete. In order to resolve the cracking issue, a preheat prior to austenitization was modeled and shown to significantly reduce the in-process stresses and reverse the residual surface stress from tension to compression. Heat-treatment responses, especially from localized heat treatments such as induction hardening, are often difficult to predict due to the directional differences of thermal expansions, contractions, and phase transformations. A predictive software like DANTE offers a means of understanding the local thermal and stress histories that a component experiences, and the reasons that cracking may or may not be an issue. In this case, cracking was an issue for conventional induction hardening, but a process modification, exposed by modeling, was discovered to successfully harden the bore of this component.

REFERENCES

[1] Induction Heating and Heat Treating, Vol 4C, ASM Handbook, V. Rudnev and G. Totten, eds., ASM Intl., 2014.

[2] Goldstein, R., Nemkov, V., Madeira, R.: Optimizing AxleScan Hardening Inductors. Industrial Heating, 12, 2007.

[3] Golovin, G., Residual Stresses and Deformation during High-Frequency Surface Hardening, Mashghiz, Moscow, 1962 (in Russian).

[4] Ferguson, B., Freborg, A., and Petrus, G., "Software Simulates Quenching", Advanced Materials and Processes, H31-H36, August (2000).

[5] Dowling, W., et al., "Development of a Carburizing and Quenching Simulation Tool: Program Overview," 2nd Int. Conference on Quenching and Control of Distortion, eds, G. Totten, et al., ASM Int., 1996.

ABOUT THE AUTHORS

Justin Sims and Charlie Li are with DANTE Solutions, Inc. in Cleveland, Ohio.


HIGH TEMPERATURE HEAT TREATMENT IS OUR SPECIALTY.
Across International equipment features targeted and precise temperature control, high quality components, and sophisticated features, all at a great price.
Across International
ACROSS INTERNATIONAL
Material Processing Equipment
AcrossInternational.com
For all your heat treatment needs, choose Across International.
888-988-0899
@acrossinternational
Online 10% off Coupon: REFERRAL20

4D HIGH-PRESSURE GAS QUENCHING

4D HPGQ is a new process that is a leap in performance vs. press quenching and allows for significant improvements to the quenching process with the main focus on reduction of distortion.

By THOMAS HART and DR. MACIEJ KORECKI

Thermal processing and quenching of steels for hardening is a well-established practice performed by various techniques over the centuries. A common thread has been the unpredictable nature of the size change during the quenching process, which is known as dimensional change or distortion. Material distortion is the undesired trade-off between the development of proper mechanical property and the necessity of rapidly quenching the material from elevated temperatures into a quenching media (i.e. brine, water, polymer, oil, gas, molten salt, etc.). Due to this compromise, users have been attempting to reduce part distortion because, once a component is hardened, it becomes very difficult and costly to remove excess material or form the part back into its original shape.

When one looks at the bearing and gearing industries, materials typically are hardened via austenitizing and quenching. Not only do these components require high hardness and wear/corrosion resistance, they also require high dimensional precision to tight tolerances as well as repeatability of results. One of the most common ways to reduce material distortion when quenching is a method by which a heated component is placed in a special fixture and a steady force is applied to the component. This allows the part to resist material deformation when the quenching media is applied. This method of quenching is known as "press quenching" and requires specialized equipment, manual or robotic handling, custom die sets and high maintenance, as well as being operator dependent to achieve consistent results.

It is well known that machining after heat treatment is one of the most costly and difficult tasks to complete in the entire manufacturing life cycle. This is why an extreme amount of engineering is devoted to the prevention of distortion of a component to ease the post heat-treatment machining operations. With the ever prevailing desire to lower the cost of raw materials and still maintain proper mechanical performance, extreme amounts of pressure are applied to the heat-treatment process to bring up the quality level of the low-cost steel. When using these low-quality steels, they are prone to high levels of distortion during the quenching process, such that they distort more than the allowable amount and either become too challenging to hard machine or are not able to be used all together. Approximately 4 percent of the price of a hardened component is attributed to the removal of post heat-treatment material to so that it meets the finished size requirements. When users can control distortion, they lower the overall cost of the component.

This paper will introduce the latest achievements in the advancement of distortion control by way of 4D high-pressure gas quenching (HPGQ) vs. press quenching. Both processes quench a single part at a time, but the 4D HPGQ process does not subject a part to any clamping forces or issues associated with liquid quenching inconsistencies. The 4D HPGQ process results in every single part being heated and quenched identically the same at surprisingly low gas pressures, thus producing extremely accurate dimensional variation with highly repeatable results. 4D HPGQ systems are easily integrated into current manufacturing environments, and the process is a revolutionary advance in quenching technology, which has been shown to reduce or even eliminate the need for expensive and difficult post hardening

1 INTRODUCTION

Quenching of steel for hardening purposes is a metallurgical process that takes place after a material is heated through its phase transformation into the austenitic range and then rapidly cooled, causing the austenite to complete a phase transformation into martensite. During the quenching process, a component experiences a very large temperature gradient throughout its geometry, and if the quench is not uniform, it results in thermal stresses and non-uniform transformation of the microstructure. When quenching is not uniform, the component will experience a large deformation in relation to the pre-heat-treated geometry. To further amplify this phenomenon, a quenching stream that penetrates a batch of parts disperses unevenly, and each part is cooled at a different rate depending on its position in the furnace.

Manufacturers over the years have attempted numerous methods to reduce distortion after quenching, as it is difficult and costly to remove excess material once the component has been hardened. One of the most popular methods of distortion control is the press quench technique, which does not employ batch quenching. Rather, it quenches one part at a time. Press quenching offers very attractive results when it comes to distortion control; however, there are unattractive aspects of the process including safety concerns (handling of hot components), environmental (oil), washing (oil removal), etc., requires special handling and equipment to quench a component after heat treatment.

2 PRESS QUENCHING

Press quenching is a process used when batch quenching provides too much distortion where a part's movement after quench exceeds the additional material left for post heat-treatment removal. These parts consist of case- and through-hardened components (gear, rings, etc.). When components are sensitive to hardening distortion, press quenching offers a versatile way to harden thin cross sections and large geometric parts. They quench one part at a time, providing dimensional stability, controlled distortion, and are very repeatable.

However, press quenching is a special quenching technique designed to control quench process to minimize distortion caused when a part is rapidly quenched after the heating cycle. One of the critical aspects of press quenching is the design and construction of the special dies. These dies are built such that they mechanically align and retain a hot plasticized part with pressure as the die restricts the desired features from distorting when quenching through its phase transformation. Oil flow across the part surface is also important in achieving the desired hardness and microstructure, and as such, the dies must be produced to balance the need for die contact and proper oil flow over the part. Common dimensions that require distortion control are runout, parallelism, concentricity, etc., and when press quenching is done in a proper manner, precise tolerances can be achieved, 0.001" - 0.002" [0.025 - 0.050mm], in relation to the pre heat-treatment dimensions.

3 HPGQ VS. OIL QUENCHING POWER

When discussing quenching, furnace systems will use various quenching processes/media to achieve the desired metallurgical properties. Based on a materials ability — or "in-ability" — to be hardened, more aggressive cooling rates may be needed to reach the required hardness as required for the components end use. The chart in Figure 2 shows the three main types of quenching oil (fast, medium, and slow) in relation to the various quenching gasses (N2, He, H2) used in thermal processing. When we look first at the quench oils, the general quenching capability range across all three oil types is 1,000 - 2,500 [W/m^2K].

The chart then shows the relationship between the type of gas and how it performs when the pressure increases in the chamber. The vertical dashed lines represent two categories in which vacuum HPGQ furnaces are generally constructed. The dashed line noted at the 14 Bar mark represents a typical single chamber batch HPGQ furnace, and the dashed line noted at the 24 Bar mark is a typical multi-chamber batch HPGQ furnace. Multi-chamber simply means it has a dedicated heating and quenching chamber where the thermally soaked hot zone is not quenched, thus allowing a multi-chamber HPGQ furnace to perform better than that of a single chamber furnace. However, a downside to the multi-chamber batch HPGQ furnace is a more complex and costlier-to-manufacture than that of a Batch HPGQ furnace. When comparing N2 Batch HPGQ vs. Oil, whereas N2 being the most common gas quenching media used for HPGQ quenching, just begins to become as strong as oil when entering the 20-24 Bar ranges. He and H2 round out the other two gasses that both perform better than N2. However, the disadvantages are that He is very costly to purchase and requires expensive reclaiming systems and H2 has its inherent safety regulations and concerns that prevent it from being used in today's quenching processes. So, where do we go from here? As you can see, 4D HPGQ when only using 9 Bar of N2 quenching gas, has capabilities that fall into the fast-oil quenching range.

4 4D HIGH PRESSURE GAS QUENCHING

4D HPGQ is a new process that allows for significant improvements to the quenching process with the main focus on reduction of distortion. Distortion reduction is achieved mainly from the use of a high-pressure gas quenching system installed in the quenching/unloading chamber (See Figure 3). The 4D HPGQ quenching platform uses a proprietary cooling manifold and chamber (Figure 4) arrangement that surrounds the part during the quenching process. This approach ensures there is a uniform flow of cooling gas across the part geometry (top, bottom, and side). When talking about top, bottom, and side quenching, this is referred to as "3D" cooling.

In order to achieve the fourth dimension when quenching, a component is placed in the quenching chamber, the proprietary cooling manifold surrounds the part, and, finally, the support table rotates the component while the N2 cooling gas flows over the part. Tyng both the 3D quenching approach with part rotation, we give birth to 4D quenching, which has the ability to further enhance quench uniformity. With 4D HPQG, it also allows for the best possible quench uniformity to be used. Current 4D quench designs allow for the use of up to 10 bar abs. quenching pressure, where shown previously (Figure 2), 4D HPGQ is now comparable to that of oil quenching without the use of helium. Also, and most importantly, since the cooling nozzles can be adjusted to fit the component's precise size and geometry, quenching can be fully optimized and distortion significantly reduced.

In addition to the aforementioned features, the parameters in Table

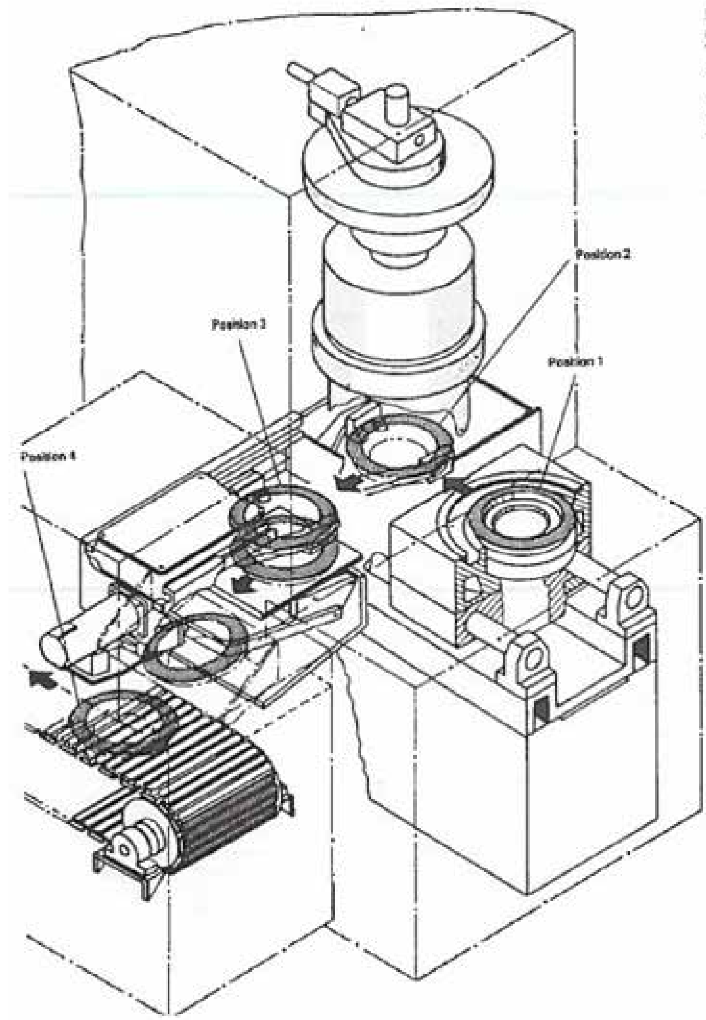


Figure 1: Illustration of a press quench machine [1].

Process control includes (but not limited to):

- oil flow
- oil pulsing
- oil dispersion
- oil quenching capability
- die shape
- die pressure
- quenching duration
- quenching rate

Description of a 4 stage Press Quench machine [Figure 1]

Stage 1 – Hot loading on lower die

Stage 2 – Upper die compression and oil flow

Stage 3 – Secondary (free) quench position

Stage 4 – Discharge tank with conveyer for final quench

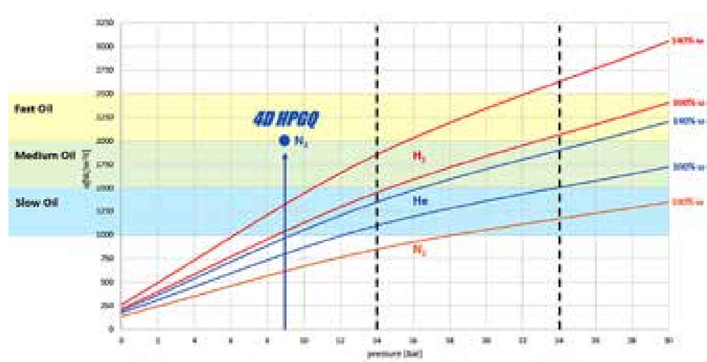


Figure 2: 4D HPGQ, batch HPGQ, and oil — quench speed relationship.

Figure 3: 4D HPGQ/unloading chamber.

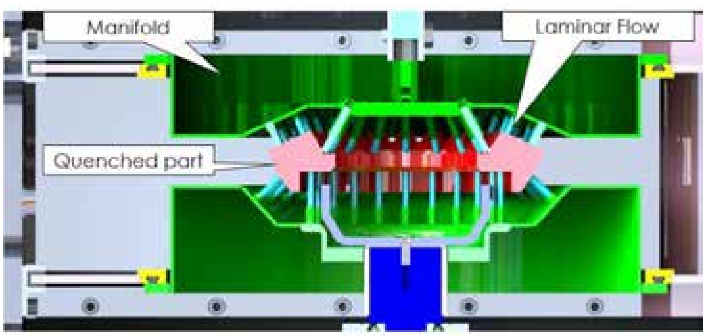


Figure 4: 4D HPGQ illustration.

Feature	Description
Quench Pressure	1 to 10 Bar abs. gas pressure
Gas Velocity	Cooling blower RPM control
Table Rotation	ON or OFF with RPM and directional adjustment
Table Oscillation	Angle adjustment
Time Dependent Gas Flow	Controlled via time in seconds

Table 1: 4D HPGQ chamber — adjustable features.

Feature	Deviation above mean
Flatness	5 – 25 µm
Axial Runout	20 – 65 µm
Ovality	10 – 38 µm

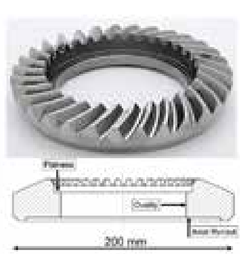


Figure 5: Hypoid ring gear.

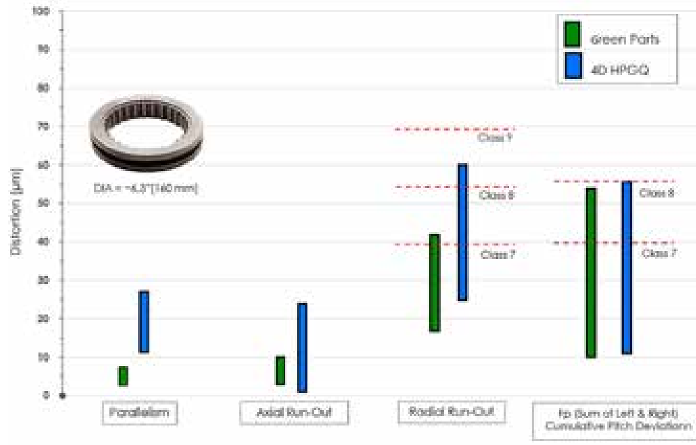


Figure 6: Ring gear — internal teeth distortion.

1 are adjustable and can be varied in their combination:

5 DISTORTION REDUCTION

In this section, we will review data from three separate examples. In example #1, the 4D HPGQ process was completed on a series of hypoid ring gears with a 7.9" [200 mm] outside diameter (Figure 5). The requirements were to carburize and quench the gears to obtain an effective case depth of 0.032" [0.8 mm] at 550 HV and tempered at 356°F [180°C].

6 4D HPGQ — HYPOID RING GEAR DISTORTION SUMMARY

In example #2, the 4D HPGQ process was completed on a ring gear with internal teeth (Figure 6) to compare distortion between pre- and post-heat-treatment conditions. Ring gear dimensions included a 6.3" [160 mm] outside diameter.

In example #3, the 4D HPGQ process was further improved upon, and tests were conducted on a coupling gear made from 8620 also with a tooth model greater than 3 (Figure 7a). The distortion was compared between pre- and post-heat-treatment conditions. The coupling gear's dimensions included a 6.0" [152 mm] outside diameter. Associated dimensions measured were radial runout, axial runout, total pitch deviation, total profile deviation, and total helix deviation.

In this trial, it shows that 4D HPGQ can maintain a 12 or higher AGMA gear class quality rating, which is on the same level as press quenching. In general, the 4D HPGQ process proved that it can produce significantly improved distortion results from the hardening process in comparison to its pre-heat-treatment features. Comparatively speaking, the UCM, when configured to its optimum quenching capacity, can provide five times the improvement in distortion to that of batch oil quenching. When distortion is reduced, it flows downstream to the subsequent machining operations, whereas machining and grinding steps can be reduced and/or even eliminated altogether.

7 CONCLUSION

Costs of post-heat-treatment material removal are significant to the overall cost of a finished component from costly machines, special tooling, and skilled labor. It is been estimated that in the mid-1990s that in the automotive industry alone, approximately $ 22.4 billion [2] was spent on the correction of distortion of hardened components. 4D HPGQ is a new process that gives end users a tool to, not only reduce the distortion of a quenched component, but they can fully optimize the quench process due to the systems flexibility and customization. In addition to the distortion benefits, the system is environmentally

Figure 7a: Coupling gear.

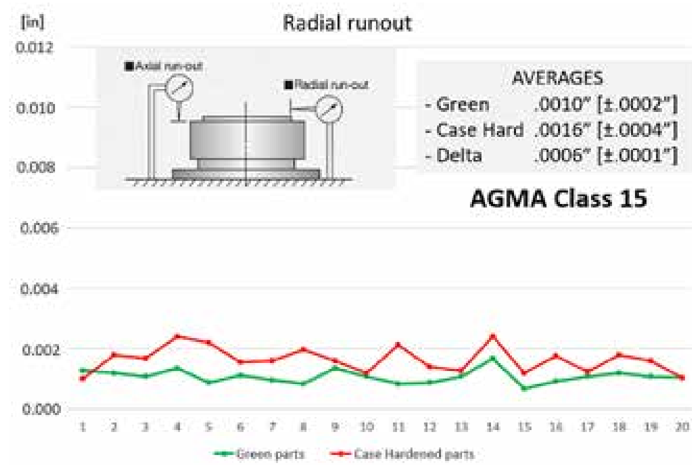


Figure 7b: Radial runout.

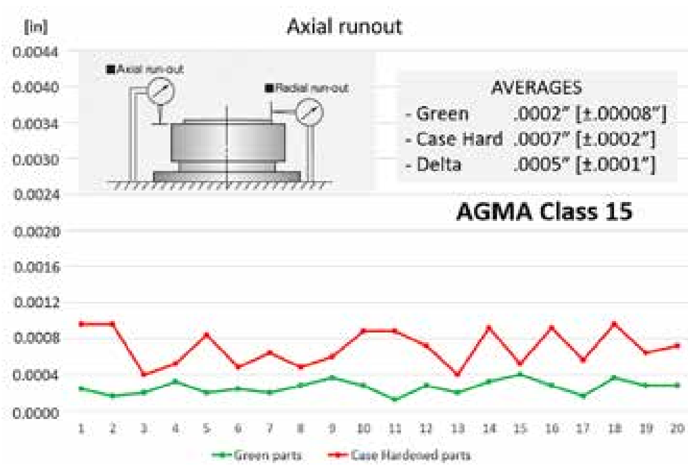


Figure 7c: Axial runout.

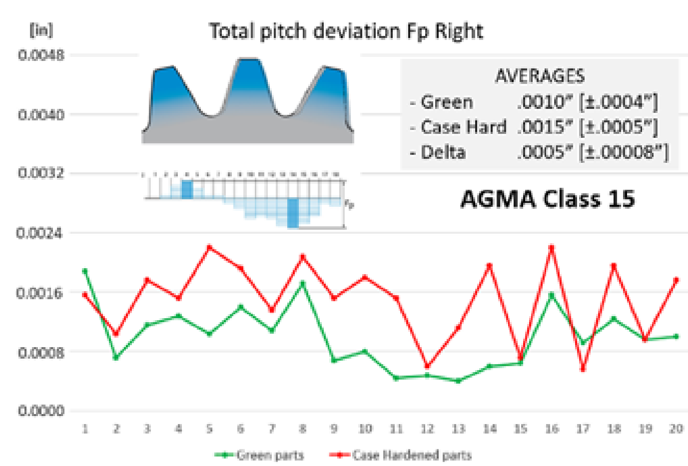


Figure 7d: Total pitch deviation.

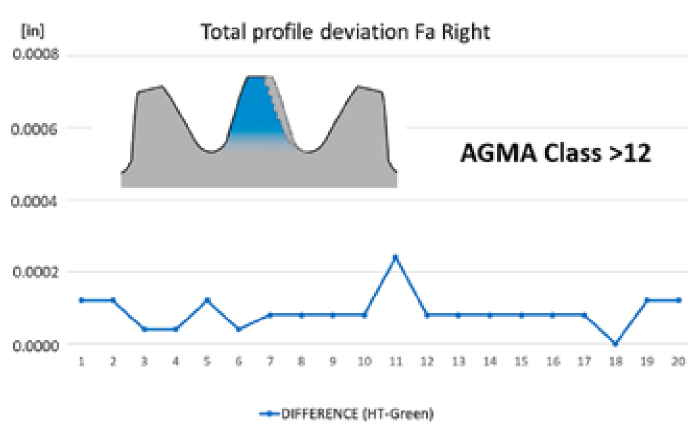


Figure 7e: Total profile deviation.

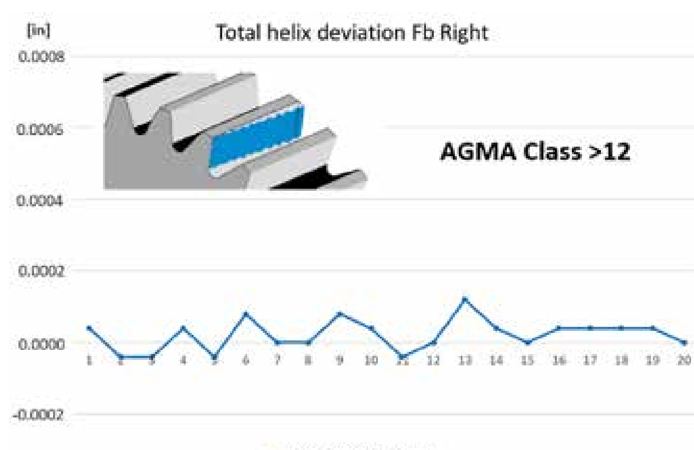


Figure 7f: Radial runout.

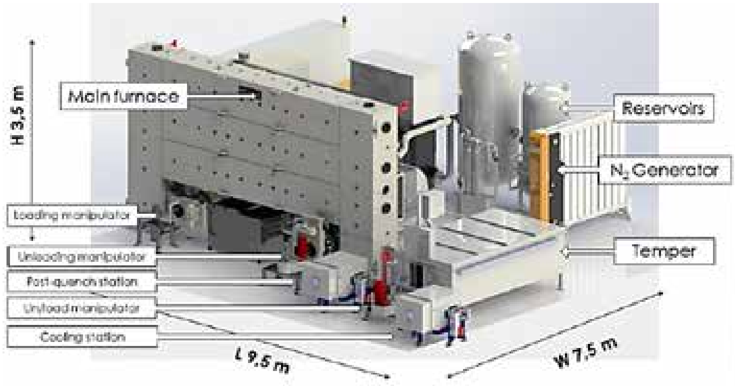
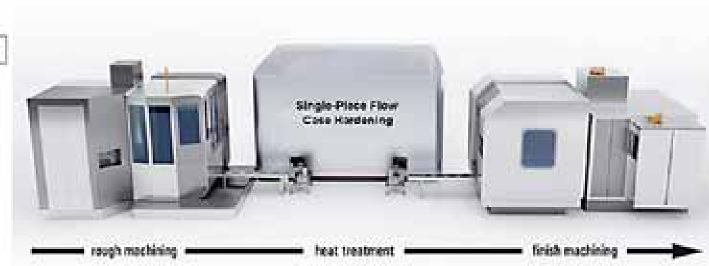


Figure 8: 4D HPGQ heat treatment work cell.



friendly, safe to operate, and can be implemented into a machining work cell (See Figure 8). When a 4D HPGQ is implemented in a machining work cell, it can eliminate the need for costly fixturing and material handling expenses associated with batch- and press-quenching platforms.

The weaknesses that come from traditional quenching platforms cannot be overcome. If more improvement is required in terms of precision and repeatability, a new tool can be used to control the process, reduce distortion, and even integrate the in-line to a production setting. This is the first and only way the real single-piece flow heat treatment with 4D quenching can be implemented, which will guarantee ideally the same process parameters for every single part in a series.

ACKNOWLEDGMENTS

Research and publications were supported by the National Centre for Research and Development as part of project no. POIR.04.01.04-00-0087/15 entitled: "Equipment for high performance and precise heat treatment with a quenching deformation reduction system for direct application in downstream production chains of mechanical gearing and bearings."

BIBLIOGRAPHY

[1] 1991, ASM Handbook, Volume 4, Heat Treating, ASM International, Quenching of Steel, p. 108.

[2] Bremen, 1995, "Economic consequences of distortion." IWT (Institut fur Werkstofftechnic), Germany.

ABOUT THE AUTHORS

Tom Hart with SECO/VACUUM and Maciej Korecki with SECO/WARWICK S.A. co-authored this presentation.

HEAT TREATMENTS AND CRITICAL QUENCHING RATES

IN ADDITIVELY MANUFACTURED AL–SI–MG ALLOYS

While heat-treating samples of LPBF-AlSi samples, their hardness response to solution annealing times and quenching rates are examined.

By LEONHARD HITZLER, STEPHAN HAFENSTEIN, FRANCISCA MENDEZ MARTIN, HELMUT CLEMENS, ENES SERT, ANDREAS ÖCHSNER, MARKUS MERKEL, and EWALD WERNER

Laser powder-bed fusion (LPBF) has significantly gained in importance and has become one of the major fabrication techniques within metal additive manufacturing. The fast cooling rates achieved in LPBF due to a relatively small melt pool on a much larger component or substrate, acting as heat sink, result in fine-grained microstructures and high oversaturation of alloying elements in the α-aluminum. Al–Si–Mg alloys thus can be effectively precipitation hardened. Moreover, the solidified material undergoes an intrinsic heat treatment, while the layers above are irradiated and the elevated temperature in the built chamber starts the clustering process of alloying elements directly after a scan track is fabricated. These silicon-magnesium clusters were observed with atom probe tomography in as-built samples. Similar beneficial clustering behavior at higher temperatures is known from the direct-aging approach in cast samples, whereby the artificial aging is performed immediately after solution annealing and quenching. Transferring this approach to LPBF samples as a possible post-heat treatment revealed that even after direct aging, the outstanding hardness of the as-built condition could, at best, be met, but for most instances, it was significantly lower. Our investigations showed that LPBF Al–Si–Mg exhibited a high dependency on the quenching rate, which is significantly more pronounced than in cast reference samples, requiring two to three times higher quenching rates after solution annealing to yield similar hardness results. This suggests that, due to the finer microstructure and the shorter diffusion path in Al–Si–Mg fabricated by LPBF, it is more challenging to achieve a metastable oversaturation necessary for precipitation hardening. This may be especially problematic in larger components.

1 INTRODUCTION

Various additive manufacturing methods for direct metal fabrication have emerged in the last decade, which can be used to fabricate directly deployable components without the necessity of a post-densification process [1,2]. Some of the most prominent representatives are the powder-bed fusion techniques, whereby a laser or electron beam is used to repetitively melt sections in a powder layer resembling the sliced approximation of the component to be manufactured, and gradually, in a layer-by-layer approach, fabricate the entire component. Within this study, the vast field is narrowed down to laser powder-bed fusion (LPBF) of hypo-eutectic aluminum silicone magnesium (Al–Si–Mg) alloys.

Al–Si–Mg alloys exhibit a unique microstructure in their as-fabricated state, whereby the macroscopic anisotropy characteristics are predominantly governed by the localized formation of silicon segregations, see Figure 1 [3,4]. This is in strong contrast to other alloys, such as austenitic stainless steels or Inconel, with their dominating characteristic being their grain morphology [5,6]. The cause for the major impact of the Si-segregations is thought to be their location, as they occur most prevalently in remolten areas, i.e., in the bonding areas between single scan tracks and subsequent layers [7]. Compared to the aluminum solid solution (-Al), the Si-segregations are brittle and prone to shear fracture [8]. Due to the layer-wise building approach in the LPBF process, these embrittlements repetitively occur every single layer and become the governing weakness, defining the observable macroscopic properties, as has been documented for tensile and compression strength as well as for the fracture toughness [8–12]. Even though these weaknesses are present, LPBF Al–Si–Mg alloys exhibit superior mechanical properties compared to their cast counterparts, at least under static loading, while the fatigue performance suffers from surface roughness and sub-surface defects [13,14]

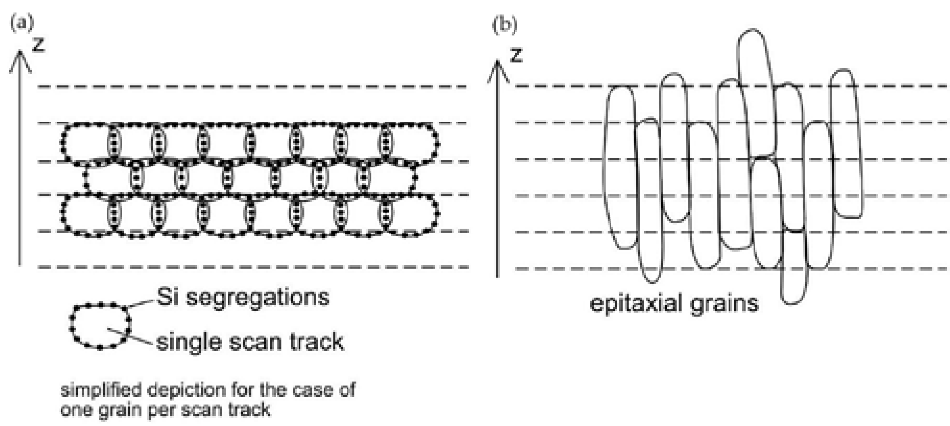


Figure 1: Simplified microstructural characteristics of (a) Al–Si–Mg and (b) stainless steel; taken from [5].

Before going into detail about attempts to mitigate the inherent weaknesses, the as-built conditions must be addressed. Due to the rapid cooling rates in LPBF, the -Al is present in a fine-grained structure and is also highly oversaturated [3]. Therefore, right after the scan track or layer is fabricated, the strength is governed by solid solution strengthening and possibly grain refinement. It is believed that subsequent heat input during the fabrication of neighboring scan tracks and subsequent layers starts the artificial aging process by first forming clusters of magnesium and silicon atoms. The stoichiometry of these clusters depends on the temperature during their formation and has a strong impact on the necessary duration of the formation of strength relevant intermetallic phases in Al–Si–Mg alloys [15-18]. From cast Al–Si–Mg, it is known that clusters formed at elevated temperatures pose a beneficial

	Scan Speed (mm/s)	Laser Power (W)	Hatch Distance (mm)	Scan Vector Length (mm)	Rotation Angle Increment ()
			AlSi7Mg0.3		
Core	1050	350	0.17	10	67
Support	900	350	–	–	–
			AlSi10Mg0.3		
Core	1150	350	0.17	10	67
Support	900	350	–	–	–
			Common		
			Preheating temperature set to 200 C		
			Layer thickness of 50 m		
			Argon environment		
			Contour irradiation and limitation window deactivated		

Table 1: Parameter sets utilized for fabrication.

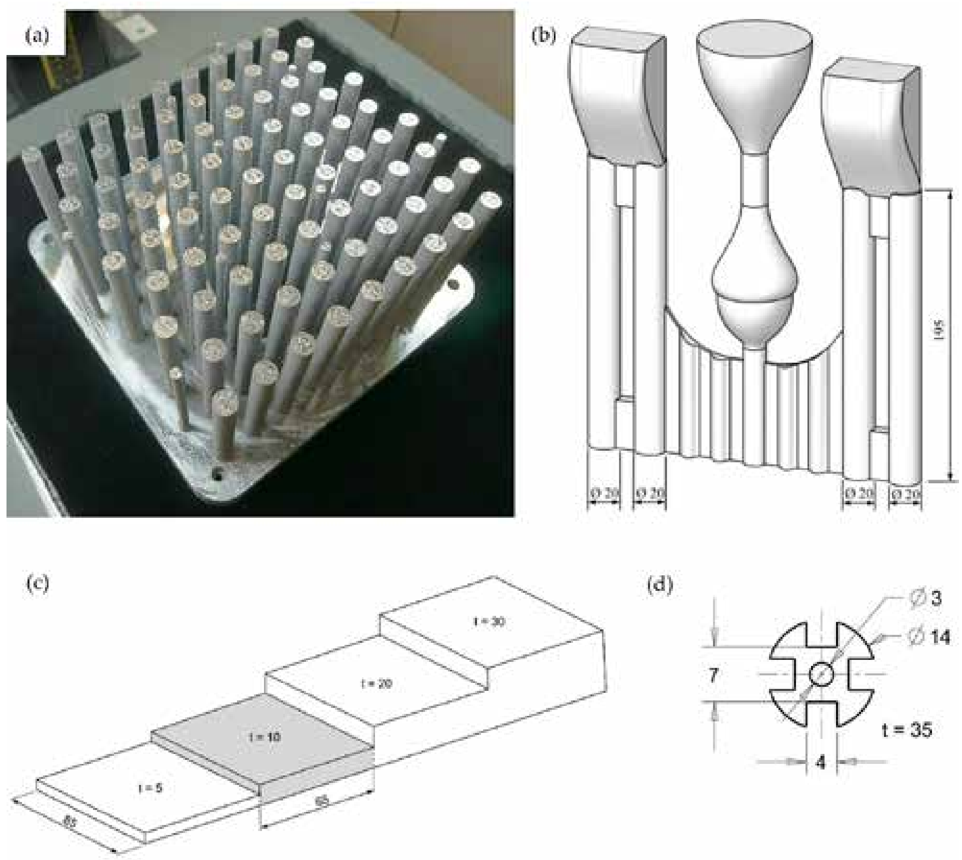


Figure 2: (a) Laser powder-bed fusion (LPBF) samples on substrate plate; (b) sand-cast assembly; (c) die-cast geometry; (d) modified sample geometry for improved quenching rates in the induction furnace.

stoichiometry and therefore enable a more effective precipitation hardening, which is used in direct-aging treatments [19, 20]. Given that the LPBF fabrication takes place in a heated environment, in addition to the cluster formation, an artificial aging of already fabricated regions occurs while the component is still being fabricated. As a result, the prevailing hardening effect in the fabricated component may be both solid solution strengthening and precipitation hardening, with precipitation hardening being the dominant strengthening mechanism in age-hardenable Al–Si–Mg alloys [8, 21]. Atom-probe studies were recently used to determine the stoichiometry of the clusters formed in early stages of the aging sequence [15, 16, 22]. It was found that the stoichiometry of the clusters depended on the temperature of their formation. If aging at elevated temperatures was performed immediately after solution annealing, the stoichiometry of the clusters favored the precipitation of strength relevant β”-precipitates. The peak aged condition can therefore be achieved by shorter artificial aging [22].

Attempting to overcome the Si-segregations via heat treatments is by no means a new approach, and numerous attempts were made in the past, albeit with limited success. Secondary artificial aging and lower annealing temperatures were shown to promote enlarged Si-particles along the remolten areas [4]. Secondary artificial aging, however, can be used to remove the variance in the hardening mechanisms [23]. In cast Al–Si–Mg solution, annealing is performed to homogenize the microstructure and to remove segregations in the material composition, which are induced during slow cooling and alterations in the solubility levels. For cast parts, the solution annealing is performed until a complete homogenization is achieved. In order to achieve a similarly stable microstructure at temperatures above 500°C, it was found that Al–Si–Mg fabricated by LPBF required a much longer solution annealing time [24]. However, such a treatment drastically transforms the microstructure, and in most cases, even after rapid quenching and artificial aging, the initial hardness and strength cannot be reached again [25-27]. On the positive side, high-cycle fatigue performance was greatly enhanced [28, 29]. None of the studies returned a conclusive statement regarding an ideal post-heat treatment for Al–Si–Mg fabricated by LPBF.

For this study, the aim was to resemble the cluster formation at elevated temperatures to achieve a best-case scenario after a solution annealing step. The materials of choice were AlSi7Mg and AlSi10Mg. For reference purposes, sand- and die-cast samples were tested as well. First trials resulted in other than expected responses of the LPBF fabricated Al–Si–Mg to the quenching rates established for cast Al–Si–Mg, and therefore the investigation was extended to capture microstructural development at varying solution annealing times and the impact of quenching rates on the precipitation hardening capabilities.

2 METHODOLOGY

2.1 LPBF Samples

Samples were fabricated in two batches: one batch with AlSi7Mg0.3 powder (supplied by LPW Technology, Cheshire, UK) and the second batch with AlSi10Mg0.3 powder (supplied by SLM Solutions AG, Lübeck, Germany). An SLM 280HL machine (SLM Solutions AG, Lübeck, Germany), equipped with a 400 W Yb-fiber-laser (Model YLR-400-WC, IPG Photonics Corporation, Oxford, Massachusetts) was used

Abbreviation	Apparatus	Treatment
AB	None	As-built condition without any additional treatment being applied
HIP-540/120-1-DA	Hot isostatic press	Solution annealed at 540 C for 120 min, quenched at a rate of 1 K/s to 165 C, aged at 165 C for 150 min; treatment performed in argon at a pressure of 75 MPa
Dil-540/X-Y-DA	Dilatometer	Solution annealed at 540 C for X min, quenched at a rate of Y K/s to 165 C, aged at 16 5 C for 150 min; treatment performed under vacuum
IF-540/2-X-DA	Induction furnace	Solution annealed at 540 C for 120 min, quenched at a rate of X K/s to 165 C, aged at 165 C for 150 min; treatment performed under vacuum
RO-540/X-Y-ZAG	Resistance furnace	Solution annealed at 540 C for X min, quenched with Y = oil quenched (OQ; oil at 20 C); water quenched (WQ; water at 20 C); hot water quenched (HWQ; water at 80 C), followed by a dwell time at room temperature of Z = 1 (1 min, immediate aging); 15 (15 min at RT); 7 d (7 days at RT), aged at 165 C for 150 min; treatment performed in air

Table 2: Detailed explanation of applied heat treatments and nomenclature.

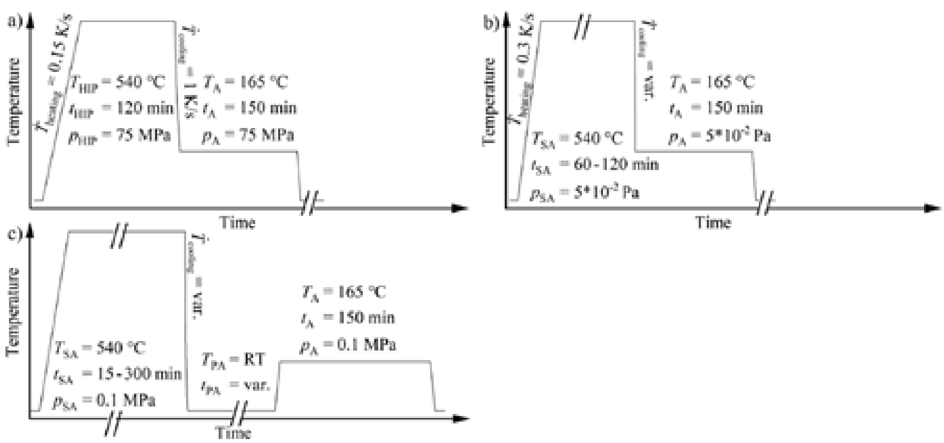


Figure 3: Schematic depiction of the applied heat treatments: (a) hot isostatic press; (b) dilatometer and induction furnace; (c) resistance furnace.

for fabrication. A detailed listing of the irradiation parameter sets and scan strategy settings is provided in Table 1.

Two kinds of samples were fabricated: small cylindrical specimens with diameter 7 mm for dilatometer tests as well as larger cylindrical specimens with diameter 14 mm. Both sample types were built in a 90-degree configuration parallel to the built direction and had a total length of 100 mm (Figure 2a).

2.2 Cast Samples

The sand-cast samples were produced by Georg Fischer AG (Schaffhausen, Switzerland) from conventional AlSi7Mg, with strontium added for refinement purposes. Hydral 40 (Vesuvius plc, London, UK) was used as a gassing agent. Samples were cast as cylindrical bars with a diameter of 20 mm and a total length of 195 mm (Figure 2b). Die-cast samples were cast by Georg Fischer AG (Switzerland) from conventional AlSi7Mg. The melt was refined with strontium, and AlTi5B1 was added for grain refinement. Casting was performed with a preheated mold (330°C) [30]. Only the 85 x 65 x 10 mm^3 sections were used in this study (shaded in Figure 2c).

2.3 Sample Nomenclature

LPBF samples are referred to as LPBF-AlSi7 and LPBF-AlSi10, respectively. Similarly, sand-cast samples are named as SC-AlSi7 and die-cast samples as CC-AlSi7.

2.4 Spark Emission Spectroscopy

The material compositions were determined on non-heat-treated samples of each batch. In order to avoid any deviations due to surface defects, the samples were ground and subsequently analyzed via spark emission spectrometry (Spectromaxx-LMX06, SPECTRO Analytical Instruments GmbH, Kleve, Germany).

2.5 Heat Treatment

The microstructure and hardness of the aluminum alloys were evaluated in various conditions, which comprised heat treatments in a quenching and deformation dilatometer (Bähr DIL 805, TA Instruments, Hüllhorst, Germany), a resistance furnace (Naber, G. Mendheim GmbH, Munich, Germany), a self-developed vacuum induction furnace (described in detail in [31]) and a hot isostatic press (EPSI, Belgium). The hot isostatic press available offers the possibility of fast cooling and has been successfully employed to perform direct-aging heat treatments on aluminum cast alloys during hot isostatic pressing [19, 20]. The direct-aging approach, which immediately continues with the artificial aging after quenching from solution annealing temperature, was used for all heat treatments, with the exception of the treatments done in the resistance furnace. The latter followed the traditional approach of removing the samples from the furnace and quenching in a cooling medium, which is followed by an artificial aging step after varying dwell times at room temperature. A complete listing of the heat treatment procedures with the introduction of the nomenclature is provided in Table 2, whereas Figure 3 shows sketches of the heat-treatment schedules.

Samples were machined to suit the employed equipment, the details on the geometries are listed in Table 3. To enhance the achievable quenching rates, a second sample geometry with an increased surface area to volume ratio was utilized in the induction oven (Figure 2d).

2.6 Hardness Evaluation

Hardness measurements were performed with two hardness testing machines. An EMCO M4U-025 (Maier Ges.m.b., Hallein, Austria) was used for Brinell hardness (HBW2.5/62.5) measurements and a Dia Testor 2 Rc (Otto Wolpert-Werke GmbH, Ludwigshafen, Germany) for Vickers hardness (HV10) measurements (for comparison purposes, the conversion tables put down in the ASTM E140-07 standard [32] were used.). Due to size restrictions on some samples, smaller Vickers indentations were chosen to allow for multiple measurements with sufficient distance in between adjacent indentations.

2.7 Micro Sections

The preparation for the microstructural characterization involved a two-stage grinding, followed by a three-stage polishing procedure. Following first inspection, the surfaces were etched with a 5% molybdic acid. Microstructure analyses were performed with a light optical microscope (Aristomet, Ernst Leitz Wetzlar GmbH, Wetzlar, Germany).

2.8 Porosity Measurements

The weight of samples was determined on a Sartorius Research R300 S scale in air and in water, using a setup based on Archimedes' principle. It should be noted that the water contained traces of additives to reduce the surface tension of the fluid to enhance the reliability of the measurements. The obtained sample densities were compared with the calculated theoretical density of the respective alloy to obtain the residual porosity.

2.9 Atom Probe Tomography

Atomic resolution in three dimensions encompassing the entire periodic system characterization and quantification is offered by the atom probe tomography (APT) technique. With APT, the clustering of silicon and magnesium atoms in the early stages of the precipitation sequence of intermetallic phases was studied. For specimen preparation, a sharp tip with less than 100 nm diameter is needed. Additively, manufactured Al–Si–Mg alloys possess Si-segregations, which mostly appear in the bonding areas between single scan tracks and subsequent layers. Since the eutectic silicon region etches differently than the matrix, an irregular shape of the tip is obtained if electrolytic polishing methods are applied. In order to achieve a regular shape of the APT tip and to ensure a defined distance to the top of the samples, the lift-out method using scanning electron microscope with a focused ion beam was used, according to [33]. By applying a low voltage, cleaning gallium implantation in the specimen was reduced. The samples were lifted out from a plane surface with a distance of 2 mm measured from the top of the standing LPBF aluminum cylinders; see Figure 2a. The measurements were done in voltage mode at 40 kHz and 200 kHz and 20% evaporation rate, using the LEAP 3000X HR system. The software IVA3.6 from Cameca (Gennevilliers, France) was used for data evaluation.

Apparatus	Sample Geometry	Quenching Rate in the Temperature Range 540 to 200 C
Dilatometer	diameter of 5 mm and 8 mm in length	up to ~33 K/s
Resistance furnace	8 mm thick slices of cylindrical samples (LPBF, sand-cast–SC); 40 30 8 mm3 (die-cast–CC)	depending on quenching media
Hot isostatic press	diameter of 16 mm and 75 mm in length diameter of 14 mm and 35 mm in length	up to ~1 K/s up to ~5 K/s
Induction furnace	diameter of 14 mm and 35 mm in length, with enlarged surface area as depicted in Figure 2d	up to ~9 K/s

Table 3: Summary of the machined sample geometries for different heat treatment apparatuses.

	Laser Powder-Bed Fused Samples			
	LPBF-AlSi7Mg0.3		LPBF-AlSi10Mg0.3	
	Average	Deviation	Average	Deviation
Si	7.947	0.343	12.483	1.180
Fe	0.134	0.026	0.205	0.006
Cu	0.021	0.002	0.004	0.000
Mn	0.008	0.005	0.015	0.005
Mg	0.373	0.017	0.297	0.122
Ni	0.023	0.007	0.021	0.002
Zn	0.125	0.026	0.048	0.009
Ti	0.012	0.012	0.034	0.006
Sr	0.001	0.001	0.003	0.000
Al	balance		balance	
	Cast samples			
	Die-Cast AlSi7Mg0.3		Sand-Cast AlSi7Mg0.3	
	Average	Deviation	Average	Deviation
Si	6.883	0.361	7.047	0.281
Fe	0.098	0.010	0.151	0.017
Cu	0.007	0.001	0.038	0.008
Mn	0.007	0.001	0.027	0.001
Mg	0.279	0.045	0.352	0.047
Ni	0.006	0.003	0.006	0.002
Zn	0.012	0.008	0.068	0.020
Ti	0.116	0.019	0.106	0.004
Sr	0.014	0.004	0.019	0.002
Al	balance		balance	

Table 4: Chemical compositions obtained via spark emission spectrometry on laser powder-bed fused and cast samples; all values in wt.%.

3 RESULTS

3.1 Chemical Compositions

In comparison to the cast samples, an increased silicon content was noted for the LPBF samples; see Table 4. Slight fluctuations in the magnesium content were evident, ranging from 0.28 wt.% for CC-AlSi7 to 0.37 wt.% for LPBF-AlSi10.

3.2 Hardness

Test series employing conventional heat treatment in a resistance furnace, with a dwell time in between heat-treatment steps (simulated by a 7-day delay between quenching and artificial aging) are depicted in Figure 4a. The hardness of die-cast (CC) and sand-cast (SC) samples stabilized at around 60 to 120 minutes of solution annealing time, after which a further increase in solution annealing time resulted in no further increase in hardness. Oil quenched samples seemed to obtain their highest hardness results after 120 minutes of solution annealing, whereas the maximum hardness of water quenched samples was observed after 60 minutes. Water quenching resulted in the highest hardness after artificial aging of all sample types, delivering better or on-par results compared to quenching in oil. To study a possible effect of fluctuations in water temperature, quenching in water of 20°C and 80°C was done, showing only minor deviations within the margins of error, included in Figure 4b. The initial hardness of CC and SC samples was raised from 70 HBW to above 80 HBW.

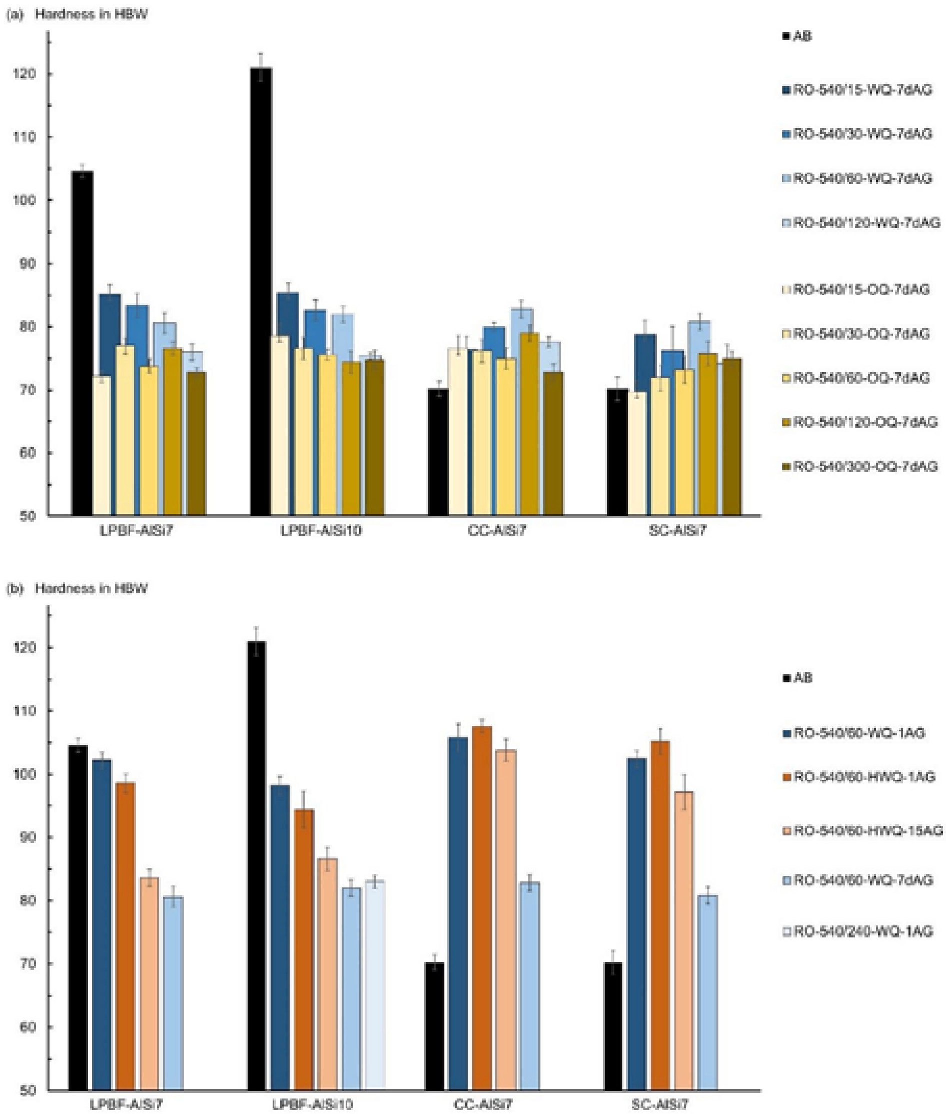


Figure 4: Hardness results for cast and laser powder-bed-fused samples in as-built (AB) and heat-treated conditions; all results refer to heat treatments in the resistance furnace (RO) and were artificially aged (AG) for 150 minutes at 165°C. Oil-quenched (OQ) and water-quenched (WQ) results at varying solution annealing times are depicted in (a); hot-water-quenched (HWQ) results and varying dwell times at room temperature are shown in (b). The used nomenclature is explained in detail in Table 2.

In contrast to the behavior of the cast samples, the hardness of the LPBF samples decreased significantly compared to their respective hardness in the as-built (AB) condition (Figure 4a). With increasing solution annealing times, the hardness after artificial aging decreased even further, facing a constant value of about 75 HBW past 120 minutes of solution annealing. Initial hardness differences between LPBF-AlSi7 and LPBF-AlSi10 remained mildly present after 15 minutes of solution annealing time but vanished at the 30 minutes mark. Immediate aging (approximately 1 minute delay between quenching and artificial aging) led to a drastically increased hardness, in the range from 98 to 106 HBW. The dwell time influence for short delays appeared to be more pronounced for LPBF samples than it was for the SC and CC samples. In comparison to the immediately aged samples, a dwell time of 15 minutes at room temperature resulted in a substantial decrease in hardness (8 to 15 HBW) for LPBF samples, whilst cast samples decreased by 4 to 8 HBW (Figure 4b). These deviations vanished after longer dwell times; samples aged after a 7-day dwell time at room temperature showed consistent hardness and a similar hardness reduction compared to the immediately aged condition. These results show that immediate aging is applicable and beneficial on LPBF samples. LPBF-AlSi7 samples reacquired their initial hardness, whereas in LPBF-AlSi10 samples, it stayed 20 HBW below their hardness in as-built condition. Cast samples, however, exhibited a more pronounced increase in hardness, due to immediate aging, than LPBF samples.

Performing the HIP-540/120-1-DA direct-aging heat treatment in the hot isostatic press returned unexpected results. There, the solution annealing time was set to 120 minutes due to the slower diffusion of alloying elements at increased pressure. For the maximum quenching rate of 1 K/s, the SC-AlSi7 samples acquired a hardness of about 80 HBW, which is comparable to that of conventionally heat-treated results, such as water quenched and artificially aged after longer dwell times (RO-540/120-WQ-7dAG). Large differences were evident for LPBF-AlSi10, whose hardness dropped to 54 ±1.9 HBW, resembling the hardness of AlSi10 in the absence of precipitation hardening.

Studies with the dilatometer confirmed that the LPBF samples require faster quenching rates than the SC reference samples (Figure 5). While the hardness of SC-AlSi7 remained constant above an average quenching rate of 5 K/s under vacuum condition, LPBF-AlSi7 required about 11–15 K/s to achieve similar hardness values. These results of the dilatometer tests agreed with those obtained in the induction furnace for the series LPBF-AlSi10. In short, LPBF samples showed no noteworthy precipitation hardening below a quenching rate of 2 K/s. For higher quenching rates, a linear increase of the hardness was observed until a hardness of about 100 HV was reached. Compared to the behavior of the HIP-540/120-1-DA results, both LPBF-AlSi7 and

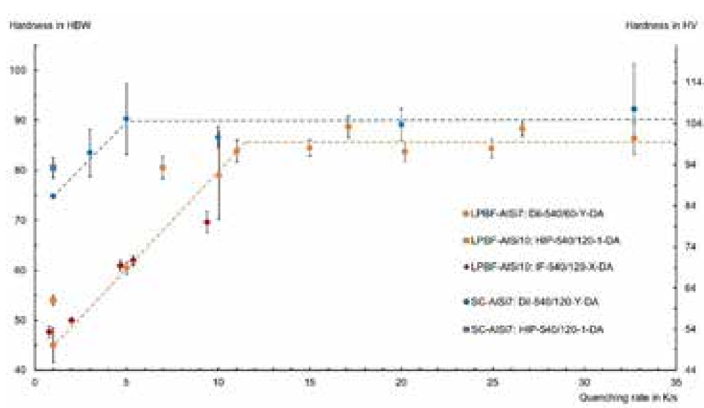


Figure 5: Hardness in dependence of the quenching rate after solution annealing followed by direct aging. The dashed levelling lines symbolize the quenching rate dependency of LPBF and SC samples. Denoted quenching rates (x-axis) refer to the average cooling rate between 535°C and 200°C.

SC-AlSi7 exhibited a higher hardness, which indicates an influence of decreased diffusion rates at increased pressure.

3.3 Micro Sections

The appearance of the microstructure for the LPBF samples in their as-built (AB) condition is closely linked to the scan track pattern employed during fabrication (Figure 6). During solution annealing, the finely dispersed Si-segregations coarsened and reduced the visibility of this interlaced pattern. The dominance of the formation of Si-segregations along the scan track boundaries was clearly observable on the 60-minute solution annealed samples. From 60 to 300 minute solution annealing time, the coarsening continued, while the dominant growth came to a hold at about 120 minutes. Magnified micro sections images illustrating the coarsening of both -Al and Si particles are depicted in Figure 7.

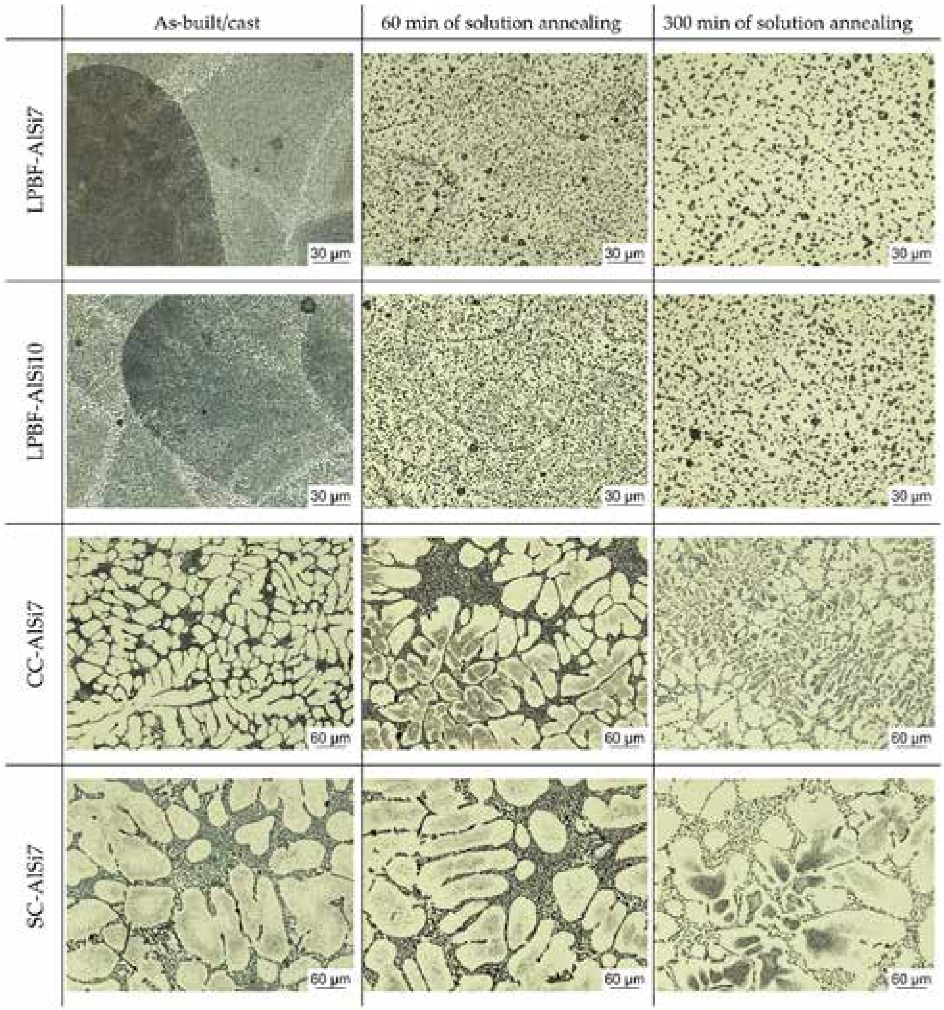


Figure 6: Comparison of microstructural evolution during heat treatment for laser powder-bed fused and cast samples in their as-built and two solution annealed conditions (60 minutes and 300 minutes at 540°C), followed by rapid quenching.

3.4 Porosity

LPBF samples exhibited a higher amount of porosity than cast samples. In the as-built condition, the porosity (Porosity was calculated via the density obtained in the Archimedes method, divided by the theoretical density of the alloy) was 0.3% in LPBF-AlSi7 and 0.7% in LPBF-AlSi10 samples. CC-AlSi7 samples had the lowest porosity with 0.001%, followed by SC-AlSi7 samples with 0.17%. The residual porosity in cast samples is caused by shrinking, and thus, voids are mostly empty.

In contrast to this, pores in LPBF-AlSi samples are likely to contain either the inert gas used during the fabrication process or hydrogen, which stems from moisture in the powder. During heat treatment, these gas-filled pores tend to expand, leading to an increase in porosity. This expansion was observed to take place within the first 30 minutes of solution annealing; samples from 30 minutes to 300 minutes of solution annealing exhibited similar porosities. The porosity of cast samples increased mildly to 0.2% in CC-AlSi7 and 0.4% in SC-AlSi7 samples. A significant increase in porosity was observed for the LPBF samples; the porosity rose to 2.9% in LPBF-AlSi7 and 2.0% in LPBF-AlSi10. Fluctuations between sample series in the induction furnace and resistance furnace were within margins of error. Hot isostatic pressing was able to improve the porosity in both cases. No remaining porosity was found in hot isostatic pressed SC-AlSi7 samples, and the porosity in LPBF-AlSi10 samples was lowered to 0.02%.

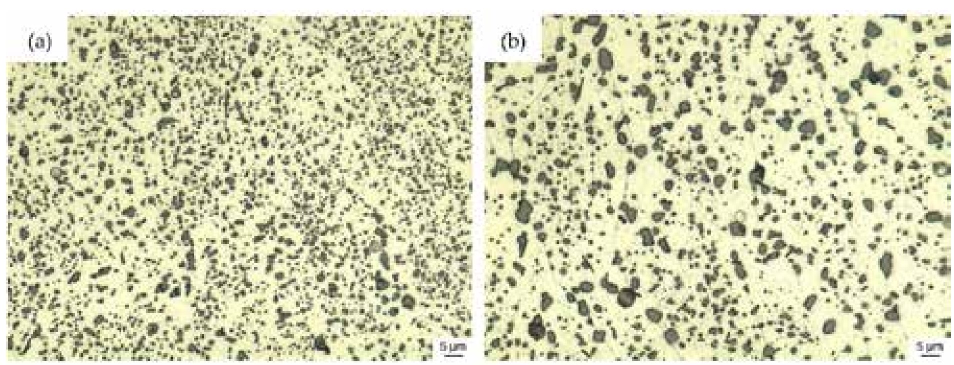


Figure 7: Micro sections of LPBF-AlSi7 samples for (a) 15-minute and (b) 60-minute solution annealing, followed by rapid quenching, illustrating coarsening for α-Al and Si particles.

3.5 Atom Probe Tomography

Figure 8 depicts the results of the atom probe tomography. Figure 8a shows the distribution of Mg atoms, while the distribution of Si Atoms is depicted in Figure 8b. The concentration isosurface for Mg is given in Figure 8d for a concentration of 3 at.% of Mg. These illustrate that the LPBF Al–Si–Mg alloy possesses clusters that contain both Si and Mg atoms. These clusters are needle shape with a diameter of about 2 to 5 nm and a length of 10 to 15 nm. Figure 8e is a proxigram, which illustrates the concentration of Al, Si and Mg atoms in the aluminum matrix (distance minus-2 to 0.5 nm) and the clusters (distance 0.5 to 2 nm).

4 DISCUSSION

Age-hardenable aluminum alloys processed by LPBF require faster

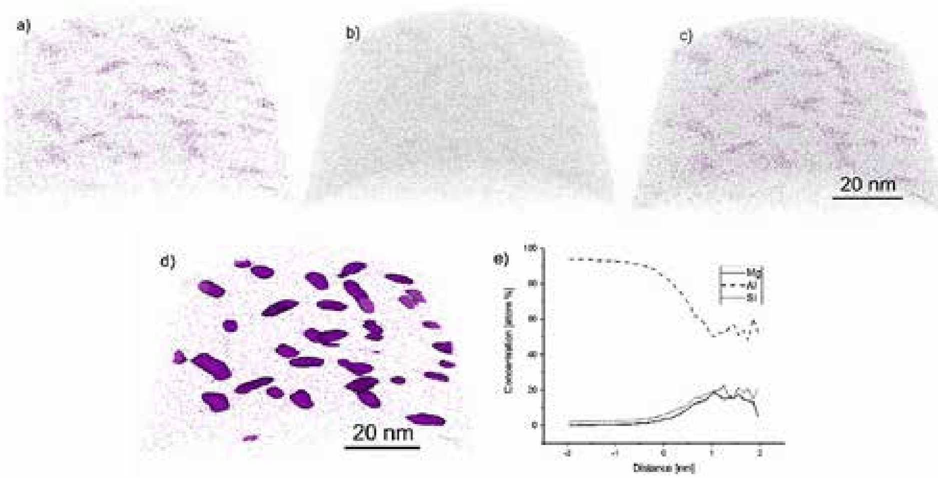


Figure 8. Atom distribution on LPBF-AlSi10 in the as-built condition for Mg (a) and Si (b) and both elements together (c). (d) shows the distribution of the Mg atoms with 3 at.% isosurface; (e) is the proxigram, showing the chemical composition for all the precipitated phases; the distance (x-axis) refers to the distance relative to the interface/isosurface. Zero indicates the interface itself, negative x-values the chemical composition outside (matrix) and positive x-values inside (cluster) the interface.

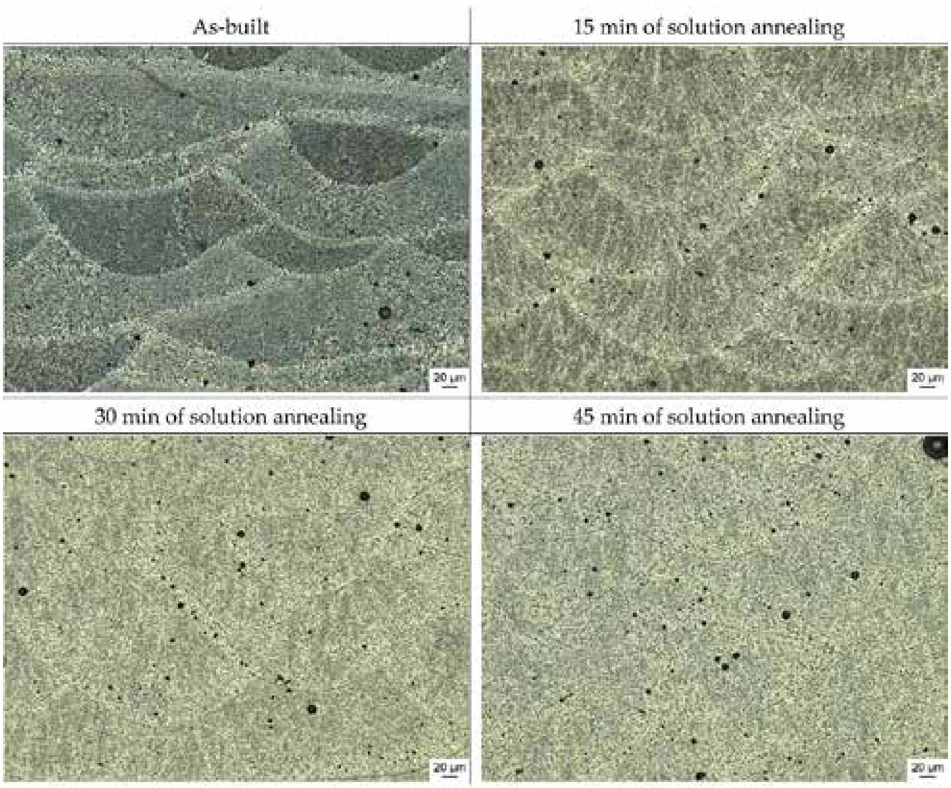


Figure 9. Development of the microstructure of laser powder-bed fused AlSi10Mg samples during solution annealing at 540°C. The gradual transformation from the distinct layered structure to a more homogeneous structure is shown.

quenching after solution annealing than their cast counterparts. A quenching rate of 1 K/s was insufficient for LPBF-AlSi10 during the combined hot isostatic pressing heat treatment to achieve an oversaturation, and as a result almost no precipitation hardening was possible. The measured hardness of 54 HBW is a typical hardness after solution annealing and quenching. The sample series RO-540/120-OQ-7dAG ranged between 56–61 HBW after quenching, prior to natural and artificial aging. LPBF samples were shown to require a cooling rate above 10 K/s in the temperature range between 535°C and 200°C under vacuum condition to allow for a sufficient precipitation hardening. A possible explanation for this could be the finer microstructure of the LPBF samples and thus the shorter diffusion paths, which lead to a faster depletion of the dissolved elements in the α-Al. Slight deviations between the dilatometer test series and those of the resistance furnace are evident, which may be attributed to the different sample sizes and the homogeneity of the temperature distribution during the heat treatment.

While T6-like heat treatments are widely promoted as homogenizing treatments for LPBF-AlSi, it was shown that in the best-case scenario, the high initial hardness of the as-built condition can be restored. However, 100 HBW was the maximum hardness reached, which is still far below the hardness of the LPBF-AlSi10 samples in their as-built condition (120 HBW). While the quenching rate above a certain value appears to become irrelevant, it is important to remember that due to the small melt pool relative to the size of the part or substrate beneath, the self-quenching effect in LPBF is much higher than the achievable quenching rates during heat treatments, and thus a further increase in hardness for much higher quenching rates cannot be ruled out [7, 34, 35]. Considering that the oversaturation reached in LPBF may be much higher than the oversaturation achieved during our heat treatments, the increased solid solution strengthening and precipitation hardening could explain the offset by 20 HBW. This assumption is supported by the particle area measurements reported by Li, et al. [36]. The total area occupied by Si particles increased by around 14% within the first 2 hours of solution annealing. With the maximum solubility of 1.65 wt.% for Si in α-Al, this increase cannot be explained. Therefore, an increased solubility or very fine-dispersed Si-particles, which likely remained hidden in the scanning electron microscope images, may be the cause. Either factor would enhance the hardness in the as-built condition and explain the significant hardness deviations seen in LPBF-AlSi10.

Atom probe tomography was performed for material regions located at a distance of 2 mm below the top face of a standing LPBF sample; see Figure 2a. The results of the atom probe tomography demonstrated that the microstructure near the top of the samples contained clusters of Si and Mg atoms. When comparing the size and shape of these clusters to relevant literature data [22], it can be noted that the clustering sequence was at least in an intermediate stage. Even though the top of the as-built material was not artificially aged for an extended period during fabrication, the region nevertheless exhibited significant atom clustering. The tendency to form such clusters is probably driven by the heat stored in the already built structure as well as in the surrounding powder bed. Due to the low heat dissipation through the powder-bed, which results from the large interface area between the powder particles and the process gas, the heat dissipa-

In contrast to the behavior of the cast samples, the hardness of the LPBF samples decreased significantly compared to their respective hardness in the as-built condition.

tion to the sides of the build chamber is low. In addition, the high number of alloying elements lowers the thermal conductivity of aluminum alloys [34,37,38]. These two effects delay the final cooldown of the built samples and allow for a sufficiently long time to start precipitation hardening. The temperature-over-time schedule after the LPBF process corresponds to a direct-aging treatment, which was shown to shorten the time for clustering of Si and Mg atoms in age-hardenable Al–Si–Mg alloys. The beneficial clustering of Si and Mg atoms is another factor contributing to the outstanding materials strength of LPBF-AlSi in the as-built condition.

The LPBF microstructure undergoes a complete transformation within the first 45 to 60 minutes of solution annealing, during which the α-Al grains coarsened significantly (Figures 7 and 9). This coarsening is a result of the absence of the finely dispersed Si-particles along the α-Al boundaries, which agglomerated to enlarged Si particles and were preferably located at the heat affected zones in the material at as-built condition. Lowering the solution annealing temperature to slow down the coarsening process was reported to be detrimental regarding achievable material strength and hardness [39].

5 CONCLUSIONS

LPBF-AlSi samples were heat treated, and their hardness response to solution annealing times and quenching rates was examined. LPBF-AlSi requires longer solution annealing times of up to 2 hours for the microstructure to stabilize. During this time, the α-Al grains coarsen significantly, and the finely dispersed Si-segregations agglomerate to larger Si-precipitates, preferably located at the heat affected zones in the material at as-built condition. While these larger Si particles mostly eliminate the directional weakening the Si-segregations cause in the as-built condition, they are too large to contribute to the material's strength. Significant differences in the required quenching rates to achieve an oversaturated condition of dissolved silicon and magnesium atoms in the aluminum matrix, which is necessary for precipitation hardening, were observed. While cast reference material required a quenching rate of about 5 K/s to achieve appreciable age-hardening under vacuum condition, the same aluminum alloy required a quenching rate of 11–15 K/s if manufactured by means of LPBF process. This large deviation may be attributed to the finer microstructure and thus shorter diffusion paths in the microstructure of LPBF fabricated material, whereby achieving a metastable oversaturation for precipitation hardening is more challenging.

The best post-heat treatment scenario was able to restore the initial hardness value. However, this was only the case for the lower alloyed AlSi7Mg alloy; for AlSi10Mg, a gap of about 20 HBW remained, with its initial hardness after fabrication being superior. The reasons for this are believed to be twofold: The fine structures in both the α-Al and the Si particles, which at this scale could be beneficial for the material strength, coarsen significantly within the first 30 minutes of solution annealing. This effect is coupled with the significantly lower quenching rates in post-heat treatments compared to the cooling rates in LPBF fabrication process and thus result in a less effective precipitation hardening.

AUTHOR CONTRIBUTIONS

Conceptualization, L.H., S.H. and E.W.; methodology, L.H., S.H. and F.M.M.; validation, S.H. and E.S.; formal analysis, L.H., S.H. and F.M.M.; investigation, S.H. and F.M.M.; resources, H.C., M.M. and E.W.; writing—original draft preparation, L.H., S.H. and F.M.M.; writing—review and editing, A.Ö., E.W.; visualization, L.H., S.H., F.M.M. and E.S.; supervision, H.C., A.Ö. and E.W.; project administration, L.H., S.H. and E.W. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGMENTS

Sincere appreciation to Michael Sedlmajer for his helpful support in the fabrication and examination of LPBF samples.

REFERENCES

[1] Hitzler, L.; Merkel, M.; Hall, W.; Öchsner, A. A review of metal fabricated with laser- and powder-bed based additive manufacturing techniques: Process, nomenclature, materials, achievable properties, and its utilization in the medical sector. Adv. Eng. Mater. 2018, 20, 1700658.

[2] DebRoy, T.; Wei, H.L.; Zuback, J.S.; Mukherjee, T.; Elmer, J.W.; Milewski, J.O.; Beese, A.M.; Wilson-Heid, A.; De, A.; Zhang, W. Additive manufacturing of metallic components – process, structure and properties. Prog. Mater. Sci. 2018, 92, 112-224.

[3] Aboulkhair, N.T.; Simonelli, M.; Parry, L.; Ashcroft, I.; Tuck, C.; Hague, R. 3D printing of Aluminium alloys: Additive Manufacturing of Aluminium alloys using selective laser melting. Prog. Mater. Sci. 2019, 106, 100578.

[4] Prashanth, K.G.; Scudino, S.; Klauss, H.J.; Surreddi, K.B.; Löber, L.; Wang, Z.; Chaubey, A.K.; Kühn, U.; Eckert, J. Microstructure and mechanical properties of Al – 12Si produced by selective laser melting: Effect of heat treatment. Mater. Sci. Eng. A 2014, 590, 153-160.

[5] Hitzler, L.; Hirsch, J.; Heine, B.; Merkel, M.; Hall, W.; Öchsner, A. On the anisotropic mechanical properties of selective laser melted stainless steel. Materials 2017, 10, 1136.

[6] Hitzler, L.; Hirsch, J.; Tomas, J.; Merkel, M.; Hall, W.; Öchsner, A. In-plane anisotropy of selective laser melted stainless steel: The importance of the rotation

angle increment and the limitation window. Proc. Inst. Mech. Eng. Part L 2019, 233, 1419-1428.

[7] Prashanth, K.G.; Eckert, J. Formation of metastable cellular microstructures in selective laser melted alloys. J. Alloys Compd. 2017, 707, 27-34.

[8] Hitzler, L.; Janousch, C.; Schanz, J.; Merkel, M.; Heine, B.; Mack, F.; Hall, W.; Öchsner, A. Direction and location dependency of selective laser melted AlSi10Mg specimens. J. Mater. Process. Technol. 2017, 243, 48-61.

[9] Hitzler, L.; Schoch, N.; Heine, B.; Merkel, M.; Hall, W.; Öchsner, A. Compressive behaviour of additively manufactured AlSi10Mg. Mat. Wiss. Werkstofftech. 2018, 49, 683-688.

[10] Hitzler, L.; Hirsch, J.; Schanz, J.; Heine, B.; Merkel, M.; Hall, W.; Öchsner, A. Fracture toughness of selective laser melted AlSi10Mg. Proc. Inst. Mech. Eng. Part L 2019, 233, 615-621.

[11] Hitzler, L.; Sert, E.; Schuch, E.; Öchsner, A.; Merkel, M.; Heine, B.; Werner, E. Fracture toughness of L-PBF fabricated aluminium-silicon: A quantitative study on the role of crack growth direction with respect to layering. Prog. Addit. Manuf. submitted. 2020.

[12] Aboulkhair, N.T.; Maskery, I.; Tuck, C.; Ashcroft, I.; Everitt, N.M. The microstructure and mechanical properties of selectively laser melted AlSi10Mg: The effect of a conventional t6-like heat treatment. Mater. Sci. Eng. A 2016, 667, 139-146.

[13] Hitzler, L.; Sert, E.; Merkel, M.; Öchsner, A.; Werner, E. Fracture toughness and fatigue strength of selective laser melted aluminium-silicon: An overview. In TMS 2019 148th Annual Meeting & Exhibition Supplemental Proceedings; Springer: Cham, Switzerland, 2019; pp. 407-412.

[14] Tang, M.; Pistorius, P.C. Oxides, porosity and fatigue performance of AlSi10Mg parts produced by selective laser melting. Int. J. Fatigue 2017, 94, 192-201.

[15] De Geuser, F.; Lefebvre, W.; Blavette, D. 3D atom probe study of solute atoms clustering during natural ageing and pre-ageing of an Al-Mg-Si alloy. Philos. Mag. Lett. 2006, 86, 227-234.

[16] Serizawa, A.; Hirosawa, S.; Sato, T. Three-dimensional atom probe characterization of nanoclusters responsible for multistep aging behavior of an Al-Mg-Si alloy. Metall. Mater. Trans. A 2008, 39, 243-251.

[17] Murali, S.; Arunkumar, Y.; Chetty, P.V.J.; Raman, K.S.; Murthy, K.S.S. The effect of preaging on the delayed aging of Al–7Si–0.3Mg. JOM 1997, 49, 29-33.

[18] Hafenstein, S.; Werner, E. Simultaneous hot isostatic pressing and solution annealing of aluminium cast alloys followed by instantaneous aging at elevated temperatures. IOP Conference Series: Materials Science and Engineering 2018, 416, 012084.

[19] Hafenstein, S.; Werner, E. Direct aging of a hot isostatically pressed A356 aluminum cast alloy. Mater. Sci. Eng. A 2019, 768.

[20] Hafenstein, S.; Werner, E. Pressure dependence of age-hardenability of aluminum cast alloys and coarsening of precipitates during hot isostatic pressing. Mater. Sci. Eng. A 2019, 757, 62-69.

[21] Buchbinder, D.; Meiners, W.; Wissenbach, K.; Poprawe, R. Selective laser melting of aluminum die-cast alloy-correlations between process parameters, solidification conditions, and resulting mechanical properties. J. Laser Appl. 2015, 27, S29205.

[22] Sha, G.; Möller, H.; Stumpf, W.E.; Xia, J.H.; Govender, G.; Ringer, S.P. Solute nanostructures and their strengthening effects in Al–7Si–0.6Mg alloy F357. Acta Mater. 2012, 60, 692-701.

[23] Sert, E.; Hitzler, L.; Heine, B.; Merkel, M.; Werner, E.; Öchsner, A. Influence of heat treatments on the microstructure and hardness of additive manufactured AlSi10Mg samples. Pract. Metallogr. 2019, 56, 91-105.

[24] Aboulkhair, N.T.; Tuck, C.; Ashcroft, I.; Maskery, I.; Everitt, N.M. On the precipitation hardening of selective laser melted AlSi10Mg. Metall. Mater. Trans. A 2015, 46, 3337-3341.

[25] Tang, M. Inclusions, Porosity, and Fatigue of AlSi10Mg Parts Produced by Selective Laser Melting. Ph.D. Thesis, Carnegie Mellon University, Pittsburgh, PA, USA, 1 April 2017.

[26] Aboulkhair, N.T. Additive Manufacture of an Aluminium Alloy: Processing, Microstructure, and Mechanical Properties. Ph.D. Thesis, University of Nottingham, Nottingham, UK, 29 July 2016.

[27] Hitzler, L.; Charles, A.; Öchsner, A. The influence of post-heat-treatments on the tensile strength and surface hardness of selective laser melted AlSi10Mg. Defect Diffus. Forum 2016, 370, 171-176

[28] Aboulkhair, N.T.; Maskery, I.; Tuck, C.; Ashcroft, I.; Everitt, N.M. Improving the fatigue behaviour of a selectively laser melted aluminium alloy: Influence of heat treatment and surface quality. Mater. Des. 2016, 104, 174-182.

[29] Brandl, E.; Heckenberger, U.; Holzinger, V.; Buchbinder, D. Additive manufactured AlSi10Mg samples using selective laser melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. Mater. Des. 2012, 34, 159-169.

[30] Brummer, M. Wärmebehandelndes heißisostatisches Pressen von Aluminiumgusslegierungen. Ph.D. Thesis, Technical University Munich, Munich, Germany, 22 May 2013.

[31] Hafenstein, S. Heißisostatisches Pressen von Aluminiumgusslegierungen mit integrierter Wärmebehandlung; Springer: Wiesbaden, Germany, 2019.

[32] E140–12b: Standard Hardness conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness and Scleroscope Hardness; ASTM International: West Conshohocken, PA, USA, 2007.

[33] Saxey, D.W.; Cairney, J.M.; McGrouther, D.; Honma, T.; Ringer, S.P. Atom probe specimen fabrication methods using a dual fib/sem. Ultramicroscopy 2007, 107, 756-760.

[34] Kimura, T.; Nakamoto, T.; Mizuno, M.; Araki, H. Effect of silicon content on densification, mechanical and thermal properties of al-xsi binary alloys fabricated using selective laser melting. Mater. Sci. Eng. A 2017, 682, 593-602.

[35] Jägle, E.A.; Sheng, Z.; Wu, L.; Lu, L.; Risse, J.; Weisheit, A.; Raabe, D. Precipitation reactions in age-hardenable alloys during laser additive manufacturing. JOM 2016, 68, 943-949.

[36] Li, X.P.; Wang, X.J.; Saunders, M.; Suvorova, A.; Zhang, L.C.; Liu, Y.J.; Fang, M.H.; Huang, Z.H.; Sercombe, T.B. A selective laser melting and solution heat treatment refined Al–12Si alloy with a controllable ultrafine eutectic microstructure and 25% tensile ductility. Acta Mater. 2015, 95, 74-82.

[37] Hafenstein, S.; Brummer, M.; Ahlfors, M.; Werner, E. Combined hot isostatic pressing and heat treatment of aluminum A356 cast alloys. HTM J. Heat Treat. Mater. 2016, 71, 117-124.

[38] Hafenstein, S.; Werner, E.; Wilzer, J.; Theisen, W.; Weber, S.; Sunderkötter, C.; Bachmann, M. Influence of temperature and tempering conditions on thermal conductivity of hot work tool steels for hot stamping applications. Steel Res. Int. 2015, 86, 1628-1635.

[39] Iturrioz, A.; Gil, E.; Petite, M.M.; Garciandia, F.; Mancisidor, A.M.; San Sebastian, M. Selective laser melting of alsi10mg alloy: Influence of heat treatment condition on mechanical properties and microstructure. Weld. World 2018, 62, 885-892.

ABOUT THE AUTHORS

Leonhard Hitzler, Stephan Hafenstein, and Ewald Werner are with the Institute of Materials Science and Mechanics of Materials, Technical University Munich, 85748 Garching, Germany. Francisca Mendez Martin and Helmut Clemensare are with the Department of Materials Science, Montanuniversität Leoben, 8700 Leoben, Austria. Enes Sert and Andreas Öchsner are with the Faculty of Mechanical Engineering, Esslingen University of Applied Sciences, 73728 Esslingen, Germany. Markus Merkel is with the Institute for Virtual Product Development, Aalen University of Applied Sciences, 73430 Aalen, Germany.

JOFRA CALIBRATION

CALIBRATIONS WITH QUALITY AND REPEATABILITY

JOFRA is one of the world's leading manufacturers and developers of calibration instruments for temperature, pressure, and process signals for temperature sensors. (Courtesy: JOFRA Calibration)

JOFRA Calibration manufactures and develops calibration instruments for temperature, pressure, and process signals, as well as temperature sensors for both operations and R&D.

By KENNETH CARTER, Thermal Processing editor

It goes without saying that in order for an oven to function correctly, it's crucial that it is reaching and maintaining the proper temperatures throughout. Without the correct temperatures, batches of product could be ruined, resulting in lost production, lost time, and — most importantly — lost revenue.

For JOFRA Calibration, being able to supply accurate and repeatable results with ease is what makes the company's high-precision calibrators an important tool in the heat-treat industry.

"What distinguishes JOFRA is that it's always been about portability and ease-of-use, where the user can save time," said Thomas Hansen, vice president of sales and marketing for AMETEK Sensor, Test and Calibration. "When you do these calibrations, they can often take quite a long time. To calibrate a sensor accurately, the calibrator has to heat up to different temperatures during the calibration, then stabilize and take measurements. When doing this repetitively, it is imperative the process is repeatable so you get confidence in the results. What we incorporate into our instruments is to eliminate the human error and any environmental factors, for example if ambient temperatures vary, combined with speed and accuracy. Time is money to our users."

To that end, JOFRA is one of the world's leading manufacturers and developers of calibration instruments for temperature, pressure, and process signals for temperature sensors both from a commercial and a technological point of view, including the portable dry-block temperature calibrator, which the company invented in the 1980s.

WIDE RANGE OF PRODUCTS

JOFRA's temperature calibrators can range from minus 100 degrees C up to 1,200 degrees C for its high-temperature calibrator, according to Hansen.

"And we have a number of different dryblock calibrators in between, basically covering that whole range," he said. "1,200 degrees C is the limit of what we do. We could do higher, but that becomes a very, very small niche market."

Calibrating the sensors at the process temperature is paramount; however, it is JOFRA's portable instrumentation that allows users to save time and basically eliminate the causes of error that are typically seen with onsite calibrations, according to Hansen.

"The alternative is taking it back into the laboratory and calibrating the thermocouple in a bath," he said. "Although in a bath, the temperature limit is 300 degrees C and not anywhere near the heat-treat temperatures employed, 1,200 degrees C for steel and typically 660 degrees C for aluminum. It's a very high level of control we have when we do calibration on the thermocouples."

JOFRA's philosophy is basically to ensure its customers achieve consistent quality and avoid downtime, according to Hansen.

"So, you have to have full confidence in the process temperature when heat treating," he said. "You need to know there are no errors that can induce uncertainty as to your thermocouple's performance: Has it drifted; is it accurate enough; do I need to replace it, and so forth? You can trust it. And that doesn't only pertain to heat treating, but there's a core value that we apply to that."

Some of JOFRA's customers use the company's calibrators to test new alloys. (Courtesy: JOFRA Calibration)

NEWEST PRODUCT

And JOFRA continues to push the envelope with its newest CTC-1205 calibrator, according to Hansen.

"It's basically an improvement over what we had previously," he said. "We've extended the temperature range, increased the accuracy to ±2 degrees C at 1,200 degrees C. For productivity, we have added functionality in terms of programmable temperature steps and automatic switch testing. You can program the unit, and it'll run through all of the steps. You can do a full run with the temperature calculator without anybody having to set different temperature points."

In addition to the CTC-1205, Hansen pointed out that JOFRA also offers the CTC-660.

"The CTC-660 is typically for aluminum types of heat treating, whereas the CTC-1205 is for all of the other metals," he said. "Those are the two main models we sell in the heat-treat industry."

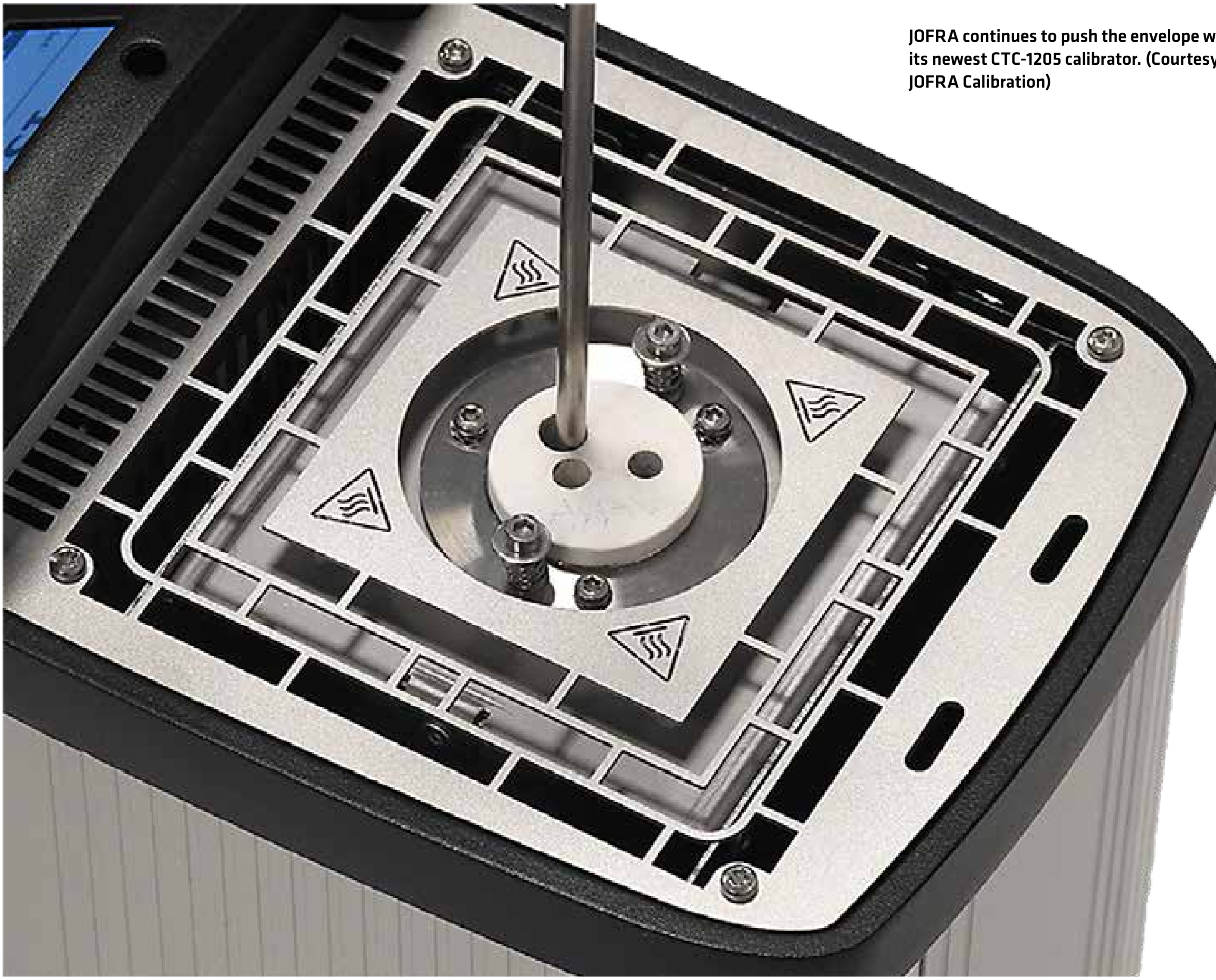
Some of JOFRA's customers even use the company's calibrators to test new alloys, according to Hansen.

"They will subject quarter-inch rods of new alloys to different temperatures, intervals, and heat profiles to evaluate the resulting physical properties," he said. "Some have more than 20 of these temperature calibrators in their laboratory, not for calibration, but to test new materials."

INNOVATIVE PUSH

JOFRA continues to push the limits of what its calibrators can do, according to Hansen.

"We're at a point now, in terms of the accuracy, where we are well within the industry requirements," he said. "Actually, we're at 2.0 degrees C with an external reference sensor. And we've reached this at 1,200 degrees C, which seems to cover the requirements of the heat-



JOFRA continues to push the envelope with its newest CTC-1205 calibrator. (Courtesy: JOFRA Calibration)

treat industry. We could extend it to 1,400 degrees C, but our voice of customer analysis did not indicate a need for this."

As far as base functionality is concerned, Hansen said JOFRA remains ahead of the industry.

"A lot of what we're concentrating on is this repeatability and saving time, which comes back to automating the process and basically making it easy to eliminate errors," he said. "That's how we are evolving with industries, but particularly with the heat-treat industry."

OFFERING CUSTOMIZATION

JOFRA also is involved with customized work when the need arises.

"Typically, the challenges that we have, particularly for heat treat, relate back to the inserts," he said. "In this dry block, you have an insert. It's a drilled insert that matches the probes that you put into it. Often, the challenge we see is developing inserts that can accommodate multiple sensors, so you can calibrate all in one while ensuring that there is a uniform temperature distribution in the insert and thus accurate results."

35 YEARS OF DEVELOPMENT

JOFRA's innovation through the years has spurred the creation of many instruments for calibration, starting with its original temperature calibrator in 1984.

"That was really unique to the world," Hansen said. "Previously, for

"If the market is there for heat treat at higher temperatures or more accuracy, then that's where we will go."

extreme temperatures, ovens were used to generate a certain temperature, but without a precise control loop. In 1984, we introduced the first commercially available dry-block. The JOFRA dry-block calibrator provided a safer alternative with higher repeatability and with a full control loop, so it quickly became popular throughout the world. One of the ways that we stay competitive is to stay ahead on what we feel is important in terms of providing high quality instrumentation to save time and ensure confidence in the temperature related process."

As part of that competitive edge, JOFRA developed the first microprocessor-based dry block calibrator a few years later, according to Hansen. And even more recently, JOFRA developed the first dual zone dry block.

"Dual zone means we control both the top and the bottom of the calibrator to achieve a very uniform temperature inside, whereas many dry blocks will just control temperature at the bottom of the insert where you have the sensing element of the thermocouple; furthermore, our temperature control is developed uniquely for the temperature range and not an off-the-shelf temperature controller," he said. "Another first in terms of new technology is what we call MVI, or Mains Variance Immunity. The instruments are used in areas with a lot of rotating and electrical machinery that causes spikes in the mains power. This can influence the calibrator and induce errors. Mains variance immunity is therefore implemented on all our calibrators, so even if you have a power connection with spikes, the instrument still remains extremely stable."

MORE BREAKTHROUGHS

Adding to its repertoire of products, in 2006, JOFRA introduced a breakthrough in its dry block technology, resulting in a patent for a calibrator that can achieve minus 90 degrees C.

"It just shows our commitment to pushing the borders of being able to calibrate on-site," he said. "And if the market is there for heat treat at higher temperatures or more accuracy, then that's where we will go."

Where JOFRA goes is rooted in its beginnings when the founders Johanne and Frank Schiessl started JOFRA — the brand name is actually a combination of their first names, according to Hansen.

"People often think it is a strange name; however, it's a unique and easily searchable name," he said. "They got the idea to make a temperature calibrator that was portable. Prior to that, all the calibrations of the thermocouples were traditionally done in calibration baths. They decided to create this dry block calibrator — with no fluids and weighing at around 10 kilos. It was something you could carry around and do calibrations onsite directly at the source."

INVESTING IN THE FUTURE

As JOFRA heads into the future, Hansen said the company continues to invest in the most innovative ways to serve its customers all around the globe.

"Heat treat is a very important industry for us," he said. "We are investing in our presence and our ability to service our customers. For example, in the U.S., we've established an ISO 17025 certified calibration laboratory at our Crystal Engineering facility in California to make sure we can turn around these dry blocks quickly for calibrations or repair. We've had that for many years in Europe and relied on third-party laboratories in the States, but our users have a preference for manufacturer calibration, and we are investing in our presence in the American market to provide a higher service level."

However, the beauty of what JOFRA offers is that the company is constantly staying on the crest of the wave in order to anticipate the market's needs, according to Hansen.

"Our quest in terms of evolving with the industry is to meet the needs for calibration," he said. "Currently, our assessment is that we meet and exceed the measurement and accuracy requirements for the heat-treat industry. However, looking forward, the demand for process automation and traceable documentation of the calibration process is increasing, and this is where our focus is turning."

And Hansen stressed that is a testament to everything JOFRA has to offer its customers.

"In terms of JOFRA, what customers typically associate us with is quality," he said. "Certainly, these are very durable instruments — sometimes too durable our sales people might say. We get products back for service and calibration that are much more than 10 years old, and that is important to us. It is an investment our customers can count on to provide many years of trouble-free calibrations and results they can depend on to keep their business efficient."

MORE INFO www.ametekcalibration.com

The CTC-660 is typically for aluminum types of heat treating. (Courtesy: JOFRA Calibration)

ADVERTISER INDEX ///

JEFF OPITZ /// PRESIDENT /// CERAMATERIALS

"By limiting the scope of products on graphiteinsulation.com, we can focus on some of the more technical aspects of insulating a graphite hot zone."

Tell us about GraphiteInsulation.com?
GraphiteInsulation.com is a vehicle for us to narrow our focus to graphite insulating products, mostly used for vacuum heat treatment inside graphite hot zones. By focusing on this product category, the site allows engineers, maintenance managers, and procurement personnel to research and directly purchase a selection of materials and parts for graphite hot zones. We are certainly not the first company to offer these materials, but our mission was to curate the most user-friendly website in the industry, and I believe we accomplished that. With our simple user interface, visitors can easily navigate through the site, purchase materials, request custom RFQs, download SDS sheets and technical documents all without needing to interact with a customer-service department. We wanted to empower customers by providing a low-friction platform to research and purchase these materials, so they can focus immediately on the task at hand.

What prompted the development of a specialized website?
We identified a need in the thermal-processing industry for a site dedicated exclusively to those utilizing graphite insulation along with the ancillary products commonly utilized with graphite insulation such as graphite foil, carbon composite channels, graphite adhesives, graphite coatings, and machined graphite components. Often times, a customer can be overwhelmed with the breadth of our material offering on our primary website www.ceramaterials.com. By limiting the scope of products on graphiteinsulation.com, we can focus on some of the more technical aspects of insulating a graphite hot zone. There are many ways to maximize the performance of a furnace, and choosing the correct insulation package is critical to maximizing processing efficiency. There are times when we find that customers are using a more expensive option when they could achieve the same performance with a lower-cost graphite insulation. If you are only reaching temperatures of 2,000°C, for instance, you probably do not need to use a Rayon based material. Rebuilding a hot zone carries a significant price tag, and we want to help our customer base save costs wherever possible. The website also makes us easier to find in the crowded arena of high-temperature insulation providers.

What does Graphite Insulation offer the industry?
We stock and distribute a wide range of graphite-based insulating solutions, with both PAN and Rayon fiber precursors in a range of purities and processing temperatures. In addition to rigid and soft-graphite insulation, we offer furnace components made from "hard" graphite. Common furnace parts we make include hearth rails, heating elements, element connectors and supports, plates, nozzles, and fasteners. We offer a proprietary selection of graphite adhesives, coatings, and graphite-treatment options. Additionally, we stock a broad selection of CFC U Channels, L Channels, and fasteners in both metric and imperial options. We also offer reverse engineering and drafting services. Customers can mail us the physical parts they need made, and we will reverse engineer them. We then provide a completed CAD drawing for their records should they need them made again; this is especially useful for maintenance managers. Our carbon cordage is available in two different weave patterns: standard weave and tight weave. We also design and produce monolithic furnace liners and susceptor supports.

What sets Graphite Insulation apart from its competition?
The amount of material options we offer in this space is unparalleled; very rarely does a company offer both PAN and Rayon-based material. The number of "off the shelf" products we stock in our warehouse is another way we differentiate ourselves. Most of the items we list on our website carry a two- to three-day lead time, while other companies have a four- to five-week lead time on these same items. This includes rolls of soft carbon and graphite insulation, rigid boards with and without foil facing, and the aforementioned line of adhesives, coatings, and fasteners. We allow for easy access to technical information, shoot our own high-quality product photos, and have partnerships with manufacturing facilities here in the U.S., as well as abroad. The flexibility in our supply chain allows us constant access to inventory and faster response times than our competition. Our sales team responds to incoming inquiries expeditiously, and our pricing is among the most competitive in the country.

How will Graphite Insulation advance the heat-treat industry?
The website never closes, and our team processes orders in real time, ensuring first-rate service and short lead times. As the industry continues toward a digital environment, we will be a steady presence.

How do you see Graphite Insulation growing in the coming years?
We continue to stay up-to-date with industry trends and innovate through technical prowess. We are developing a mirror site to serve the market in Mexico. Our ties to the aerospace, defense, and medical industries position us to grow as these industries grow.

MORE INFO graphiteinsulation.com


THIN FILM DISTILLATION SYSTEMS
THE CLEAR CHOICE FOR PURIFYING EXTRACTS
@acrossintl
888-988-0899
AcrossInternational.com
ACROSS
INTERNATIONAL
Material Processing Equipment