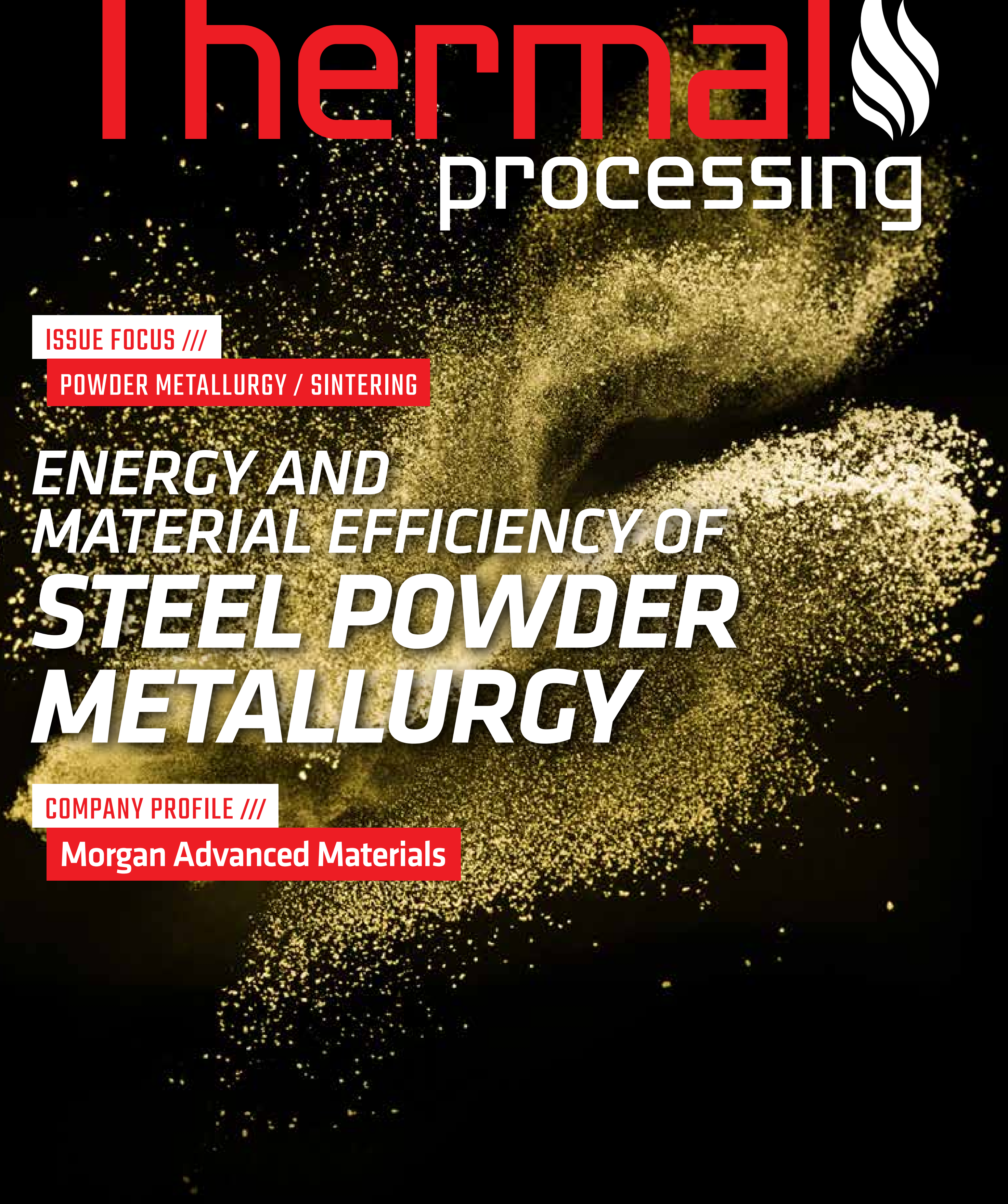
Technologies and Processes for the Advancement of Materials

# Thermal processing



ISSUE FOCUS ///

POWDER METALLURGY / SINTERING

## ENERGY AND MATERIAL EFFICIENCY OF STEEL POWDER METALLURGY

COMPANY PROFILE ///

Morgan Advanced Materials

JUNE 2019
thermalprocessing.com

# Leading the Way in On-Site Controlled Atmosphere Generators

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## DX® | Exothermic Gas Generators



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- Built-in maintenance features
- Fully tested prior to shipment

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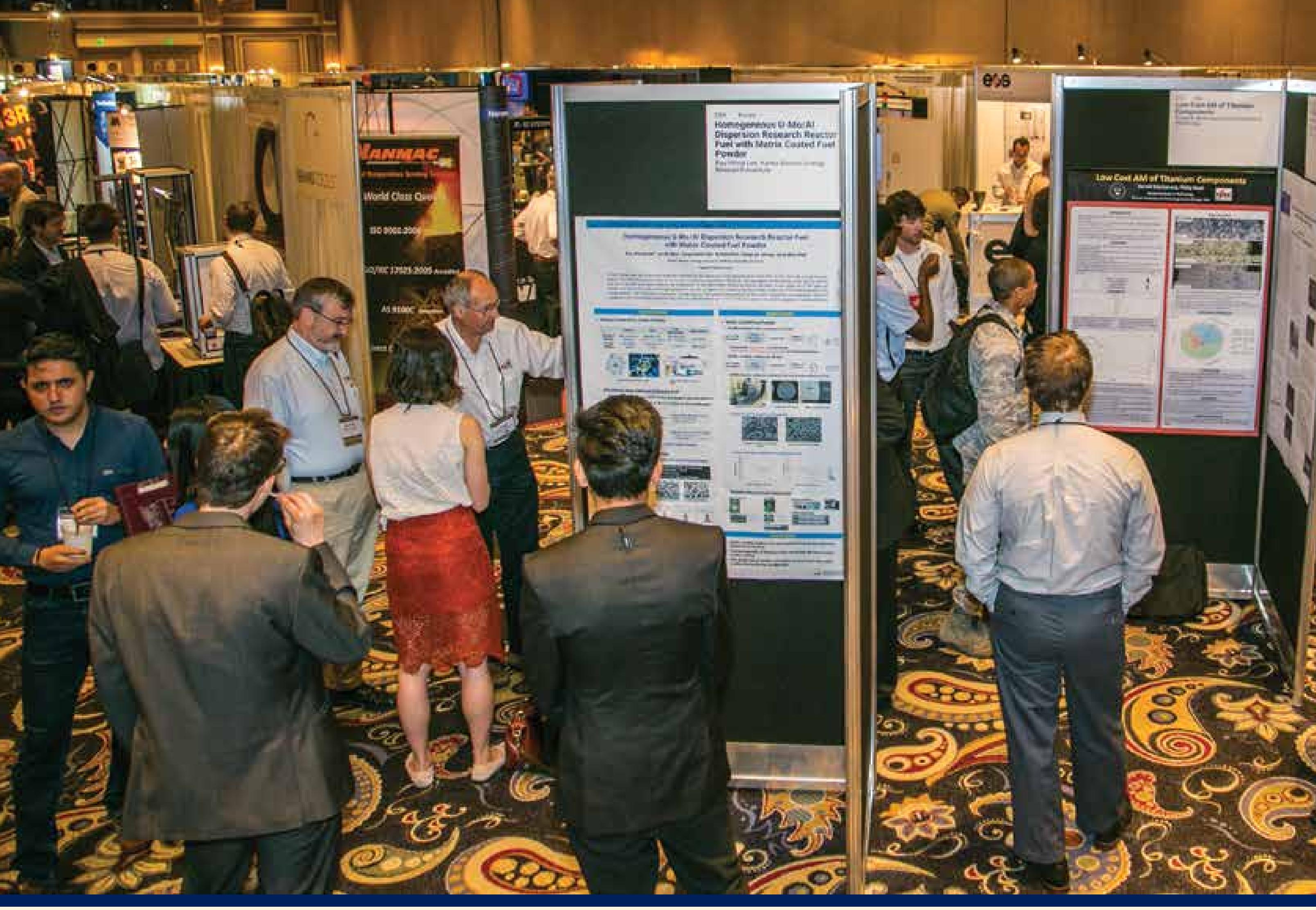

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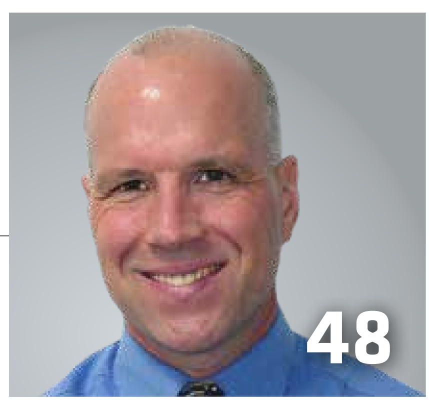
ASSOCIATE DIRECTOR, BUSINESS DEVELOPMENT /// PRAXAIR, INC.



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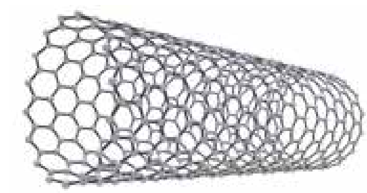

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## FROM THE EDITOR ///

# This month, sintering is literally out of this world

It's hard to forget about heat-treating if you have to live through a summer in the South. And although the official beginning of summer is in just a few days, in the South, summer feels like it begins around February 12.

If you're experiencing some summer heat right now, we have a few articles in this month's issue that might keep your mind off it — at least for a while.

One interesting article is from the experts from the Metal Powder Industries Federation about a process that is literally out of this world. It deals with sintering experiments taking place on the International Space Station. The research is looking to determine whether more uniform sintering is possible without gravity's influence.

Powder metallurgy also takes front and center this month. Experts from the University of Cambridge look at how powder metallurgy processes provide opportunities that are not available using more conventional materials.

In addition to our feature articles, this issue also gives you plenty of heat-treating information from our regular columnists and more.

And on that note, I have to be the bearer of bittersweet news. Hot Seat columnist Jack Titus has decided to "retire" as a regular contributor to *Thermal Processing*.

Jack began writing for our sister publication, *Gear Solutions*, in 2011. When *Thermal Processing* began, he graciously agreed to begin writing his column for that magazine.

Whether he was writing for *Gear Solutions* or *Thermal Processing*, his 58 years of expertise and wisdom in the field of heat treating was vast — and it showed. He claims he never considered himself a writer, but his ability to convey complex processes in an easy-to-understand forum was a testament that he was, indeed, a writer — and a good one.

Your knowledge and experience will be missed, not just by the staff at *Thermal Processing*, but by our many readers who enjoyed your columns every month.

Thanks again, Jack.

Please enjoy Jack's final column, as well as the rest of this month's offerings. I'm sure you'll find something that interests you.

In the meantime, stay cool, and thanks for reading!

**KENNETH CARTER, EDITOR**
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**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.

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OPERATIONS


Working conditions, career perspectives, employee training, and supporting individual development are some of the criteria describing the behavior worthy of the Reliable Employer title received by Seco/Warwick. (Courtesy: Seco/Warwick)

## Seco/Warwick named Reliable Employer of the Year

Seco/Warwick, a global leader in metal heat treatment technology, received the Reliable Employer of the Year award, becoming one of the best employers in Poland.

The Jury of the Reliable Employer of the Year competition selects the best employers, in particular those who promote interesting HR solutions and share their experience. Working conditions, career perspectives, employee training, and supporting individual development are some of the criteria describing the behavior worthy of the Reliable Employer title.

Kinga Mann, HR director at Seco/Warwick, collected the award confirming clear and reliable activity of the company in terms of employment on behalf of Seco/Warwick during the Reliable Employer Gala.

"The Reliable Employer of the Year award is a huge distinction, as it confirms that we are taking appropriate steps towards improving job satisfaction," Mann said.

People decide and want to decide about the success of an organization, therefore building employee engagement is a must. And so, two years ago Seco/Warwick conducted a study on employee engagement and satisfaction, which has led to developing, in cooperation with the working groups, a comprehensive HR program. Today, employee engagement has become decisive for achieving competitive advantage as well as an important factor contributing to the organizational climate. This is why participation of employees in defining the company's needs has always been so important to Seco/Warwick Group.

"We are building on a reliable foundation. This motto reflects the company's philosophy across multiple levels. Not only in terms of developing new technologies, but also in creating new jobs. Reliability is a strong part of the company's DNA; after all, Seco/Warwick is where 'Invention Meets Reliability," said Katarzyna Sawka, Seco/Warwick group marketing director.

"At Seco/Warwick we do not guess, we talk, listen, and change. We create a common space for everybody – Seco/Sphere. We invite there everybody who have passion in the DNA, interesting projects at heart, and challenge flowing through their veins," Sawka said.

Investing in the employees, supporting initiatives that make it possible to release their potential, as well as access to the state-of-the-art technologies and permanent cooperation with training establishments support development and improving qualifications. Providing the employees with comfortable working conditions translates into their well-being, higher efficiency at work, and engagement, which constitutes the grounds for perfect operations of the entire company.

**MORE INFO** www.secowarwick.com

## Vaisala offers probe for rapidly changing environments

Vaisala, the global leader in environmental and industrial measurements, launched the HUMICAP® Humidity and Temperature Probe HMP9, a compact smart probe with superior response time. It is designed for industrial applications, where fast thermal response, measurement performance, and long-term stability are essential.

The Vaisala HMP9 incorporates world-leading measurement accuracy and superb thermal response time in a compact package — the truly mini-sized probe weighs only a few grams and the probe head is only 5 mm of diameter. The low thermal mass of the probe offers superior response time compared to other capacitive humidity measurement products on the market. Probe's compact

**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.

**The truly mini-sized HMP9 smart probe weighs only a few grams and the probe head is only 5 mm in diameter. (Courtesy: Vaisala)**

body does not only adapt to the changing environment faster, but it also makes it suitable for installation in tight spaces, which allows measurements in locations where traditional-sized probes cannot fit.

The HMP9 is designed for rapidly changing or condensing environments. The smart probe is optimized for dryers, air handling units, test chambers, or other systems and processes where measuring humidity can make a difference in saving energy or improving the product or the process. It also brings added value to a variety of applications or locations with temperatures below 120°C (248°F) that don't involve high pressure, but where the accurate humidity and temperature measurement is a critical factor.

In addition to relative humidity and temperature, the HMP9 smart probe provides measurements of other calculated humidity parameters, such as dew point temperature, wet-bulb temperature, absolute humidity, mixing ratio, water concentration, water vapor pressure, and enthalpy.

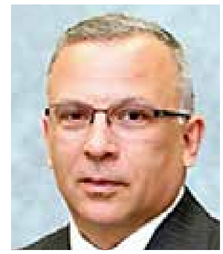
The new HMP9 contains a HUMICAP® sensor that provides industry-standard humidity measurement performance. The sensor is equipped with chemical purge option, which heats the sensor to remove harmful chemicals, helping to maintain measurement accuracy between calibrations.

Vaisala HMP9 is a part of the modular Indigo product family and is plug-and-play compatible with the Indigo 201 and Indigo 202 transmitters, which can provide local displays and analog or digital outputs when needed. The probe can also be used as a standalone probe with a digital Modbus RTU output. For on-site configuration, diagnostics, and calibration the probe can be connected to Vaisala Insight PC Software.

**MORE INFO** www.vaisala.com

# Gasbarre announces new business development director

Gasbarre Products, Inc. has announced the hiring of John Blauser as business development manager for Gasbarre Precision Tooling. Blauser is responsible for maximizing tooling sales as well as developing a strategic plan for the acquisition of new customers and the retention of existing customers.



**John Blauser**

Blauser comes to Gasbarre with many years of experience in the powder metal industry, nearly 17 years his previous role alone. He is a current APMI West Penn Chapter Member and past chairman, and on both the APMI Tech Board and the APMI Conference Committee. He is also a member of the APMI Board of Directors.

CEO Alex Gasbarre said, "We are very excited to have John on board with Gasbarre. His experience with materials and powder compaction will provide invaluable benefits to our tooling sales and marketing efforts. John's enthusiasm and commitment to the PM industry, coupled with Gasbarre's design and tool-making capabilities, will make a huge impact on the growth of Gasbarre's precision tooling product line."

**MORE INFO** www.gasbarre.com

## L&L Special Furnace introduces new product catalog

L&L Special Furnace Co., Inc. has announced a newly designed 32-page catalog describing its full line of furnaces, ovens, and quench tanks.

L&L is a family-owned manufacturing and service business in operation for more than 60 years. It designs and builds high-temperature furnaces, ovens, kilns, quench tanks, and heat-treating systems. L&L specializes in batch production furnaces and ovens, particularly for applications requiring high uniformity and controlled atmosphere. The company sells and services equipment worldwide.

L&L has grown steadily over the years, with a good reputation in the ceramics and precision heat-treating markets. Its quality products are used by many of the largest and most prestigious companies in the aerospace, heat treating, ceramics, and automotive industries.

Manufacturing, sales and engineering are integrated in one 17,000-square-foot facility 10 miles south of Philadelphia.

**MORE INFO** www.llfurnace.com


**L&L Special Furnace specializes in precise temperature control and uniformity with its ovens and quench tanks.**

**Grieve's No. 944 is an electric cabinet oven that heats to 750°F. (Courtesy: Grieve)**

## Grieve markets 750°F electric cabinet oven for sintering

Grieve oven No. 944 is a 750°F electrically heated cabinet oven currently used for sintering operations at a customer's facility.

Workspace dimensions measure 44"W x 30"D x 60"H. 30kW installed in Incoloy-sheathed tubular heating elements heat the oven, while a 2000 CFM, 2 HP recirculating blower provides a horizontal airflow to the workload.

The Grieve cabinet oven features 6" insulated walls, aluminized steel exterior, Type 430 stainless steel interior, and four 20"W x 28"H independent doors for easy access to the workspace. Eight removable loading pans are provided for each door compartment (32 pans total).

No. 944 has a digital-indicating temperature controller, manual reset excess temperature controller with separate contactors, and 10" diameter circular chart recorder onboard. In addition, four timers, each with a pilot light and door interlock, are included to individually time the heating process in each compartment.

**MORE INFO** www.grievecorp.com

## Parts2clean 2019: Future-proofing the cleaning of parts

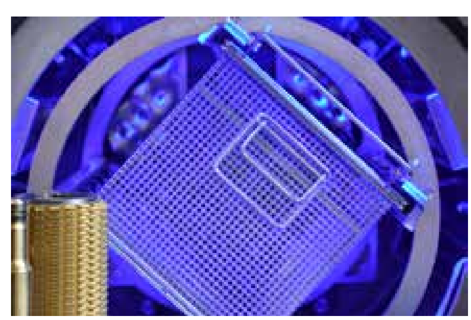
The industrial parts and surface cleaning sector is facing new challenges. Parts2clean 2019 shows how these challenges can be met.

The 17th International Trade Fair for Industrial Parts and Surface Cleaning will be October 22-24, 2019, at the Stuttgart Exhibition Center.

Areas of interest include new and modified production technologies, such as the growing use of adhesive bonding, laser welding and coating processes, as well as the additive manufacturing of components. At the same time, there is increased demand for the cleaning of workpieces made from new materials or material combinations, as well as complete assemblies. And then there are the tougher regulatory requirements, such as those contained in the new European Medical Device Regulation (MDR).

These changes are forcing business enterprises to review existing processes and question old ways of doing things.

"Parts2clean is the perfect place for businesses to gather the information they need for positive changes," said Olaf Daebler, global director of parts2clean at Deutsche Messe. "As a global meeting place for industry, the event and its exhibitors not only showcase the very latest technological advances in industrial



**The 17th International Trade Fair for Industrial Parts and Surface Cleaning will be October 22-24, 2019, at the Stuttgart Exhibition Center. (Courtesy: Deutsche Messe)**

parts and surface cleaning, but also highlight key trends and offer best-fit solutions.”

The range of leading-edge exhibits allows visitors from many different sectors such as the car and component supply industry, medical technology, mechanical engineering, the aerospace industry, precision engineering and micro-engineering, optics, electronics, semi-conductors, and coating technology — to find the information they need quickly and easily.

For the all-over or selective cleaning of surfaces in various situations, there is now a growing trend toward the use of dry-cleaning processes. Parts2clean reflects this development with a broad range of offerings, which include systems for CO2 snow blasting, plasma cleaning, laser cleaning, vibratory finishing, and cleaning with compressed air. Visitors will be looking for the right process engineering and plant to remove particulates or film-type contaminants efficiently and with consistent results in order to comply with new, tougher standards. Others will be more interested in technology for cleaning parts made from new materials, parts with highly complex geometries, and more. Also popular with visitors will be solutions for the control and monitoring of cleaning, rinsing and drying processes, as well as systems for checking and quantifying the degree of cleanliness achieved.

**MORE INFO** www.parts2clean.de

## Seco/Warwick provides fire-resistance system

Seco/Warwick will provide a fire resistance test system at Aluprof S.A., a leading producer of aluminum architectural systems in Europe. The laboratory furnace will test the fire resistance for vertical elements of building structures (glazed walls and curtain walls) at a temperature up to 1,200°C.

The Seco/Warwick system will allow Aluprof to test new products such as windows, doors, and façade systems before launching. Aluprof is now equipped to test many construction solutions that will ensure the highest quality product, and obtain the appropriate certification. The equipment was delivered with a specialized afterburning system to follow high environmental protection requirements.

**The Seco/Warwick system will allow Aluprof to test new products such as windows, doors, and façade systems before launching. (Courtesy: Seco/Warwick)**

“Our customer’s safety is our top priority at Aluprof S.A. We invested in the Seco/Warwick technology because the equipment was designed to meet our standards for performance tests, and meet or exceed our local environmental standards,” said Jacek Cholewa, investment director at Aluprof.

“We are serious about the design, engineering, and manufacturing of our furnaces for laboratory applications, as we are passionate about producing solutions that are both safe and reliable. We are proud to produce this technology with the power to make lives safer," said Jaros aw Talerzak, VP, thermal heat treatment furnace dystems at Seco/Warwick.

Seco/Warwick laboratory furnaces are the optimal solution in the implementation of structural fire resistance tests of building and ship constructions, horizontal and vertical components, and safes. Seco/Warwick has the technology expertise to design, engineer, and manufacture equipment to perform a wide variety of experimental processes in a manner that gives the user maximum flexibility.

**MORE INFO** www.secowarwick.com

## Tenova to supply aluminum strip processing line

**The new Tenova aluminum strip processing line will process automotive and aircraft aluminum alloys, family series 2XXX, 5XXX, 6XXX, and 7XXX. (Courtesy: Tenova)**

Henan Tongren Aluminium Co. Ltd, a Chinese manufacturer specialized in the production of aluminum products, awarded Tenova, a company of the Techint Group specialized in innovative solutions for the metals and mining industries, with a new contract for a continuous annealing and chemical pretreatment line for processing strip coils for aluminum market, to be realized in Sanmenxia, Henan Province (China). This adds up to more than 15 references in China, North America, and Europe.

The new line will process automotive and aircraft aluminum alloys, family series 2XXX, 5XXX, 6XXX, and 7XXX.

The line is equipped with double unwinding pay off reels and with a tailor-made stitcher with automatic spray lubrication system. The entry side trimmer is equipped with integrated scrap chopper. The alkali degreasing section is made by a spray tunnel with multistage cascade rinsing section. Entry and exit loopers are horizontal type with double winch motorization.

Chemical process starts with an acid tunnel etching section, followed by a no-rinse spray titanium zirconium passivation, and a squeegee roll coater for oxylane product for automotive adhesive bonding application.

The exit side includes a tension leveler, a pre-aging furnace, an automatic surface inspection system, a dry lube smelter, and a rotary shear. The thermal portion is supplied by EBNER Industrieofenbau GmbH, one of the leading suppliers in floating furnaces for aluminum heat-treatment processing line plant, consolidating the partnership between the two companies in aluminum lines and increasing their top record reference list worldwide.

The line is expected to start its production at the beginning of 2021.

"This new order confirms Tenova as a reliable partner in processing lines for aluminum thanks to our continuous effort to improve the design and the manufacture of its supply to maximize line availability," said Nicola Cavero, Tenova senior vice president Italimpianti & Strip Processing, "We were chosen among several companies and are very proud of this new contract that consolidates our leadership in this field."

**MORE INFO** www.tenova.com

## Wisconsin Oven ships five standard draw batch ovens

Wisconsin Oven Corporation has shipped five electrically heated standard draw batch series ovens to East Carolina Metal Treating in Raleigh, North Carolina.

The standard draw batch ovens (SDB ovens) will be used for stress relieving and have maximum oven operating temperatures of 1,250°F. The basket dimensions of each oven are 2 feet wide x 3 feet long x 2 feet high. Guaranteed temperature uniformity of ±10°F at set points 300°F, 750°F, and 1,250°F was documented with a nine-point temperature uniformity survey in empty oven chambers under static operating conditions.

Wisconsin Oven's heat-treat ovens and tempering furnaces (SDB Series) come in 10 standard sizes and are available as either gas-fired or electrically heated in four temperature ranges. The SDB series features heavy-duty furnace construction, including a plate steel outer shell, a reinforced steel plate oven front, a lined inner shell, and exterior structural reinforcements as required.

"East Carolina Metal Treating has been incredible to work with, and we look forward to working with them for many years to come. ECMT even filmed the installation process for these five batch ovens, and the time lapse video is available to watch on both the WOC and ECMT Facebook pages," said Mark Schahczinski, sales engineer

Unique features of each draw batch oven include:

› Temperature uniformity of ±10°F at 300°F, 750°F, and 1,250°F.
› 3,600 CFM @ 3 HP recirculation system.
› 36 kW heating system with SSR control.
› One vertical lift, pneumatically oper-


**The standard draw batch ovens (SDB ovens) will be used for stress relieving and have maximum oven operating temperatures of 1,250°F. (Courtesy: Wisconsin Oven)**

ated door.

› Digital UPC Protherm 470 process controller.

› Digital Eurotherm 3204 oven high limit controller.

These standard draw batch ovens were fully factory tested and adjusted prior to shipment. All safety interlocks were checked for proper operation and the equipment was operated at the normal and maximum operating temperatures. An extensive quality assurance check list was completed to ensure the equipment met all Wisconsin Oven quality standards.

**MORE INFO** www.wisoven.com

## Thermcraft develops equipment to meet customer specs

Thermcraft Incorporated manufacturers high-quality thermal processing equipment. The international company manufactures low and high temperature laboratory furnaces, production furnaces, vacuum formed ceramic fiber heaters, cast heaters, heater coils, air heaters, ovens, kilns and diffusion heaters.

Diffusion is the process of molecules moving from an area of high concentration to a low one. It occurs routinely within and between liquids, gases, and solids in daily life. This process is exploited by diffusion furnaces, which elevate the temperature of workpieces and introduce gaseous elements to encourage solid state diffusion.

Solid state diffusion occurs when molecules of a substance mix with a host solid at the atomic level. This mechanism of diffusion was a scientific curiosity for many years but has since become an integral process in semiconductor manufacturing.

A diffusion furnace is a thermal processing unit with a cylindrical heating chamber that can be oriented either horizontally or vertically. This enables circular workpieces to be processed with outstanding thermal uniformity due to the equidistant surfaces radiating heat. They can also function under partial vacuum conditions to ensure tight atmospheric control throughout operation. This is critical in ensuring optimal conditions for the vapor-phase to diffuse into the solid-state semiconductor without introducing undesirable impurities.

When a semiconductor wafer is treated in a diffusion furnace, it is heated to within a setpoint temperature and subjected to a flow of gaseous molecules known as the vapor-phase. This phase diffuses into the solid substrate at the atomic level, a process known as doping.

Semiconductors such as silicon (S) display unique electronic properties between those of an insulator and a conductor. Dopants are introduced to modulate those electronic properties and make them suitable for semiconductor device fabrication. They diffuse into the crystal lattice and become immobilized within the atomic structure, creating either an excess or deficiency of electrons or electron holes. This is what alters the conductivity of the semiconducting wafer.

Elements such as phosphorous (P) are commonly used to increase the number of free electrons in the wafer's atomic structure, creating what is known as an n-type semiconductor. Conversely, gallium (Ga) can be used to introduce an electron acceptor that creates extra electron-hole energy levels. This is an n-type semiconductor.

The functional differences between n- and p-type semiconductors are myriad, as are the chemical variations currently used and under exploration as dopants for intrinsic semiconductors. To learn more about how diffusion furnaces are used for electronics manufacturing, read Thermcraft Inc.'s previous blog post: "Using an Industrial Furnace for Semiconductor Device Fabrication."

Thermcraft specializes in the development of thermal insulation and circular heating elements for diffusion furnaces. It provides collars, discs, and vestibule blocks comprised of ceramic fiber packed with braided silica, which can be sized and shaped to distinct customer specifications. These are suitable for the extremely high operating temperatures of various diffusion furnace processes.

**Thermcraft specializes in the development of thermal insulation and circular heating elements for diffusion furnaces. (Courtesy: Thermcraft)**

All offerings are custom designed to meet customers' thermal requirements.

**MORE INFO** www.thermcraftinc.com

## Tenova receives follow-up order for furnace plant

OJSC MMK-METIZ, a producer of advanced steels for the automotive industry from Magnitogorsk, Russia, has placed a new contract for the expansion of the existing HPH® Bell-Type furnace plant for wire coils with Tenova LOI Thermprocess, a Tenova company, located in Essen, Germany.

OJSC MMK-METIZ, located in Magnitogorsk, Chelyabinsk region, already operates an HPH Bell-Type furnace plant supplied by Tenova LOI Thermprocess in 2014. This plant consists of two annealing bases, one heating hood, and one jet-cooling hood with a maximum net charge weight of 36 metric tons of wire rod or drawn wire coils. It uses a hydrogen/nitrogen mixture as protective gas atmosphere and features a useable diameter of 3,200 mm and a useable height of 2,700 mm.

**OJSC MMK-METIZ has placed a new contract with Tenova for the expansion of the existing HPH® Bell-Type furnace plant for wire coils. (Courtesy: Tenova)**

In the spring of 2019, a new contract was signed concerning the expansion of the existing plant by further two annealing bases, one additional heating hood, and one jet-cooling hood. The start of production of the new plant is scheduled for the beginning of 2020. Besides the spheroidization annealing of wire rod, this plant also carries out the recrystallization annealing of drawn wire coils with the HPH® (High Performance Hydrogen) annealing technology.

**MORE INFO** www.tenova.com

# Cutting tool maker buys Seco/Vacuum tempering furnace

A global manufacturer of cutting tools has purchased an additional vacuum temper furnace from Pennsylvania-based Seco/Vacuum (SVT), a Seco/Warwick company, for its North American manufacturing operations. The new furnace, which will be used for tempering and stress-relieving metal parts, is part of the company's growing manufacturing expansion and complements another commissioned earlier in 2019 at this facility.

The horizontal, front-loading furnace is purpose-built to accommodate the customer's needs with an all-metal hot zone for clean vacuum processing. As with the earlier furnaces, one of which was installed at a different facility, the new furnace includes a convection fan and a pressurized gas quench for quick cooling.

The Seco/Visory team approach enables customers to navigate complex decision paths to achieve the most effective and efficient solution.

Seco/Vacuum provides consultation, project engineering, installation, and aftermarket support from its Meadville, Pennsylvania, headquarters via the company's Seco/Visory team consulting service. Seco/Visory is a cost-free service for qualified companies. It allows heat-treaters to examine their needs, evaluate equipment options appropriate to those needs, and make an informed decision with the help of SVT's heat-treatment experts.

**MORE INFO** www.secovacusa.com

# IHEA Fall Seminar series back in Cleveland

The Industrial Heating Equipment Association (IHEA) heads to Cleveland, Ohio, for its 2019 Fall Seminars and Fall Business Conference. The event will be at the Intercontinental Cleveland, from September 24 to 26. The technical seminar series will be Tuesday and Wednesday, followed by the IHEA Fall Business Conference on Thursday.

"Cleveland has been the site of some of our most successful seminars and meetings," notes IHEA Executive Vice President Anne Goyer. "We're excited to return to an area that draws attendees interested in learning ways to continuously improve their operations."

In its 90th year, IHEA remains an industry leader by providing expert-led, unbiased training for those in the industrial thermprocessing industry. The 50th Combustion Seminar and the Safety Standards and Codes Seminar will take place concurrently over the first two days. There will also be a one-day Process Heating Seminar that will include infrared, induction, and other process-heating technologies. Attendees of all seminars will have access to IHEA's Tabletop Exhibition & Reception on the afternoon of Tuesday, September 24.

The Combustion Seminar is presented by industry professionals from leading heat-processing companies who deliver relevant information on combustion technologies. The comprehensive Safety Standards and Codes Seminar covers critical safety information for those involved with a wide range of industrial thermprocess applications as well as the 2019 updates to the NFPA 86 standard.

New this year, the Process Heating Seminar will be at a nearby IHEA member company, Selas Heat Technology. The unique venue allows attendees to experience hands-on demonstrations of the different technologies described throughout the seminar. Selas will also offer a facility tour for attendees.

The IHEA seminars and speakers always receive high marks on evaluations. Attendees often comment on the knowledgeable speakers and great tips they can apply to their processes immediately.

A few remarks from former students:

› "PowerPoint slides were very informative, and I appreciate the 'extra' information from the speakers instead of just reading the slides."

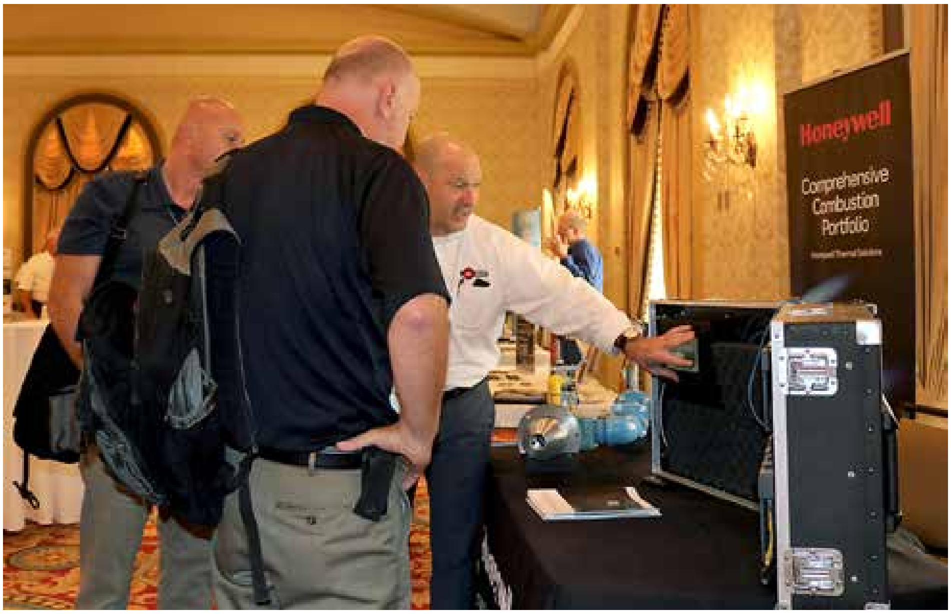
› "Very impressed all around. Great job to all the speakers."

› "Excellent seminar for someone new to combustion."

All three classes offer the perfect mix of technical information and the opportunity to attend the tabletop exhibition to interact with speakers and suppliers of the products and services discussed throughout the seminars. IHEA's Fall Seminar Series and Tabletop Exhibition are an outstanding way to lead, learn, and grow.

Furthermore, IHEA's Fall Business Conference follows the seminars in Cleveland, beginning Wednesday evening, September 25, with a social gathering to kick-off the meeting. IHEA conducts the


**Learn from the best by attending one of IHEA's Fall Seminars.**




**The IHEA seminars and speakers always receive high marks on evaluations.**

conference for the purpose of bringing member company representatives together for committee meetings and educational presentations to discuss challenges and issues of concern to members.

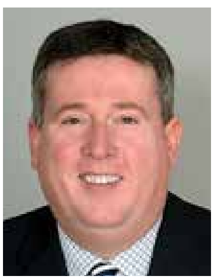
Mark your calendar for September 24-26, 2019, and watch for more details and registration information at www.ihea.org/page/fall19.

Learn from the best by attending one of IHEA's Fall Seminars. IHEA members receive significant discounts on seminars. Consider joining IHEA today to save on registration fees. End users receive four vouchers with their membership that can be used to register for seminars for FREE! Visit www.ihea.org for more information about membership and how to join!

Established in 1929 to meet the need for effective group action in promoting the interests of industrial furnace manufacturers, IHEA has expanded and includes designers and manufacturers of all types of industrial heat-processing equipment used for the melting, refining, and heat processing of ferrous and nonferrous metals and certain nonmetallic materials and heat-treatment of products made from them. Visit IHEA online at www.ihea.org and on Facebook.

# IHEA welcomes new board members

The Industrial Heating Equipment Association (IHEA) recently announced its 2019-2020 Board of Directors and Executive Officers. IHEA's president is Michael Stowe of Advanced Energy; Scott Bishop of Alabama Power Company assumes the role of vice president; and Jeff Valuck of Surface Combustion was elected treasurer. Serving as past president is Daniel Llaguno of Nutec Bickley.



**Gary Berwick**

**Bob Fincken**

**Doug Glenn**

IHEA also welcomed three new board members: Gary Berwick of Dry Coolers, Bob Fincken of Super Systems, Inc., and Doug Glenn of *Heat Treat Today.*

"At our recent annual meeting in Sarasota, Florida, we were very excited to officially appoint three new board members," said IHEA President Michael Stowe. "They will each serve a three-year term, with service through the 2022 annual meeting. These folks represent dozens of years of process heating experience across several different markets. IHEA is very fortunate to have them serving on our board."

Berwick is a veteran in the heat-treating industry with more than 30 years' experience. He has been involved with IHEA since the early 1990s and stays active through his engineered sales role with Dry Coolers. Berwick is also a member of the Metal Treating Institute and the American Society of Manufacturing. IHEA is fortunate to have Berwick's valuable contributions on the Education committee as well.

IHEA gains a respected industry professional in Fincken of Super Systems Inc. Fincken is the company's national sales manager for North America with 30 years of experience in controls and sensors. He is a great asset on IHEA's Safety Standards and Codes committee and provides input for IHEA's educational tools to support the association's knowledge base.

Publisher of *Heat Treat Today*, Glenn returns to the IHEA Board of Directors. His support of the association spans 25 years and includes everything from promotion, sponsorships, speaking engagements, and serving as a committee chair. Glenn has an extensive background in publishing, marketing, and association business. IHEA is pleased to have Glenn's dedication and commitment.

To complete the Board of Directors for 2019-2020, IHEA is proud to name those continuing their service: B.J. Bernard, Surface Combustion, Inc.; Brian Kelly, Honeywell Thermal Solutions; Francis Liebens, SOLO Swiss Group; John Podach, Fostoria Process Equipment, a div. of TPI Corp.; Jason Safarz, Selas Heat Technology Co. LLC; and John Stanley, Karl Dungs, Inc.

## IHEA 2019 CALENDAR OF EVENTS

**AUGUST 28–29**

**The Powder Coating & Curing Processes Seminar**

The day and a half Introduction to Powder Coating & Curing Processes Seminar will include classroom instruction and hands-on lab demonstrations.

› Alabama Power Technology Center | Calera, Alabama

**SEPTEMBER 24–25**

**IHEA 2019 Safety Standards & Codes Seminar**

This seminar is intended to help the attendee become better acquainted with the newly updated NFPA 86 – Standard for Ovens & Furnaces.

› InterContinental Hotel Cleveland | Cleveland, Ohio

**SEPTEMBER 24–25**

**IHEA 2019 Combustion Seminar**

The industry premier seminar for industrial process heating professionals, this two-day event offers attendees the chance to learn the latest in combustion technology and visit with industry suppliers. The IHEA Combustion Seminar is designed for persons responsible for the operation, design, selection and/or maintenance of fuel-fired industrial process furnaces and ovens.

› InterContinental Hotel Cleveland | Cleveland, Ohio

**For details on IHEA events, go to www.ihea.org/events**

TRIRATNA SHRESTHA
MANAGER OF METALLOGRAPHIC LABORATORY AND CENTRAL COATINGS LABORATORY /// METCUT RESEARCH INC.

*Applying carbon nanotube reinforced aluminum-based nanocomposite via the powder metallurgy route.*

# Enhanced properties of metal matrix nanocomposites

Application of carbon nanotube (CNT) reinforced metal matrix nanocomposite (MMNC) has been increasing rapidly since the discovery of CNT in the 1990s. These novel MMNCs are reported to have enhanced properties compared to base alloy systems. Some of the enhancements are electrical, thermal, structural, and mechanical. MMNCs are expected to find application in all industries, if it has not already been applied. CNTs have exceptional tensile strength, low thermal expansion coefficient, and low density. Aluminum, a light metal, is being reinforced with CNT to make it even lighter and improve properties of monolithic aluminum. Light materials with enhanced mechanical property have immense usage in light-weight application, especially aerospace and sports equipment. But reinforcement of aluminum with CNT has been hindered by the agglomeration of CNT because of its light weight and does not disperse uniformly in the metal matrix. In this study, aluminum (Al)/CNT nanocomposite made via the powder metallurgy route and conventionally vacuum sintered was characterized using scanning electron microscopy (SEM), nanoindentation, and differential scanning calorimetry (DSC).

Al and CNT were mixed in an argon atmosphere and ball milled for 2.5 hours. Milling with various wt.% of CNT and aluminum powder was performed. SEM study was conducted on milled samples to examine dispersion of CNT in an Al matrix. Cold compaction of milled samples was performed at various loads: 20, 22, 25, 28, and 30 tons. Archimedes' principle was used to measure density of sintered pellets. Nanoindentation technique was used to measure hardness and reduced elastic modulus. Thermal analysis of the composite was conducted with DSC.

Ball milling of Al was performed with bare Al, 0.1 percent, 0.5 percent, and 1 percent CNT. Ball-to-powder ratio was 10:1. Ball milling promotes mechanical alloying and distribution of CNT in the matrix. CNTs are prone to breakage and cold welding of powder during milling. Hence, care should be taken to control the milling parameters, such as the ball-to-powder ratio, and milling duration.

Figure 1 shows CNT embedded in a milled and compacted MMNC pellet. Compaction of milled powders was performed to obtain pellets for subsequent characterization. Compaction load was varied in Al/0.1% CNT to study its effect on density of the nanocomposite. Density of pellets increased with increasing load, as shown in Figure 2, indicating that the higher load is effective in reducing voids and porosities in the matrix. In all loading conditions, density is lower than the ideal density of aluminum, which is 2.7 g/cc. Lower density can be contributed to remaining voids, inadequate compaction, and sintering.

For conventional sintering performed in a vacuum, the reduced modulus of bare aluminum decreased with increasing sintering temperature. A similar trend was observed in Al/0.1% CNT matrix, as shown in Figure 3. Such a phenomenon is attributed to pellet matrix relaxation and release of CNT's residence stress during sintering at lower temperature. However, the Al/0.1% CNT matrix had a higher reduced modulus at all temperatures compared to bare Al, which attests the added benefit of CNT as it shares load and transfers stress during loading. CNTs are effective in load sharing by the virtue of their size, distribution, and unique larger aspect ratio. Nanohardness of bare Al matrix decreased with increasing sintering temperature, as shown in Figure 4. Nanohardness of Al/0.1% CNT matrix slightly increased for 200oC sintering but decreased at 400oC. Remarkably, nanohardness of the nanocomposites sintering at 200oC and 400oC

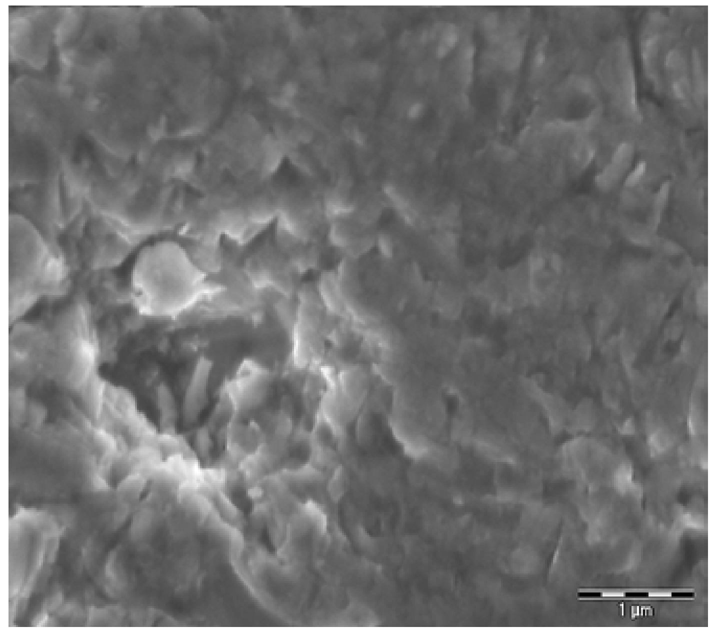



**Figure 1. SEM micrograph of compacted and sintered pellet showing embedded CNT in the Al matrix.**

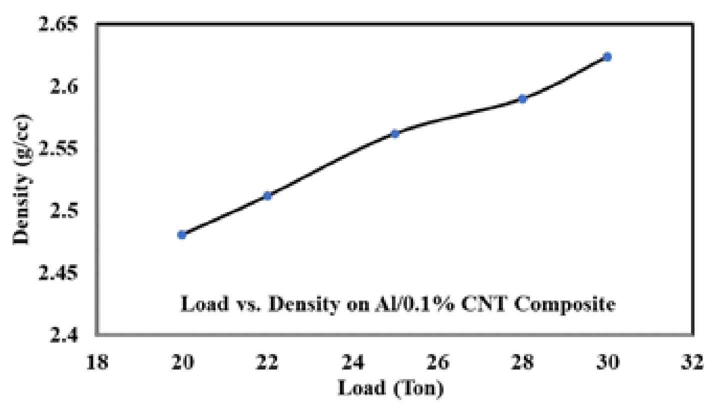
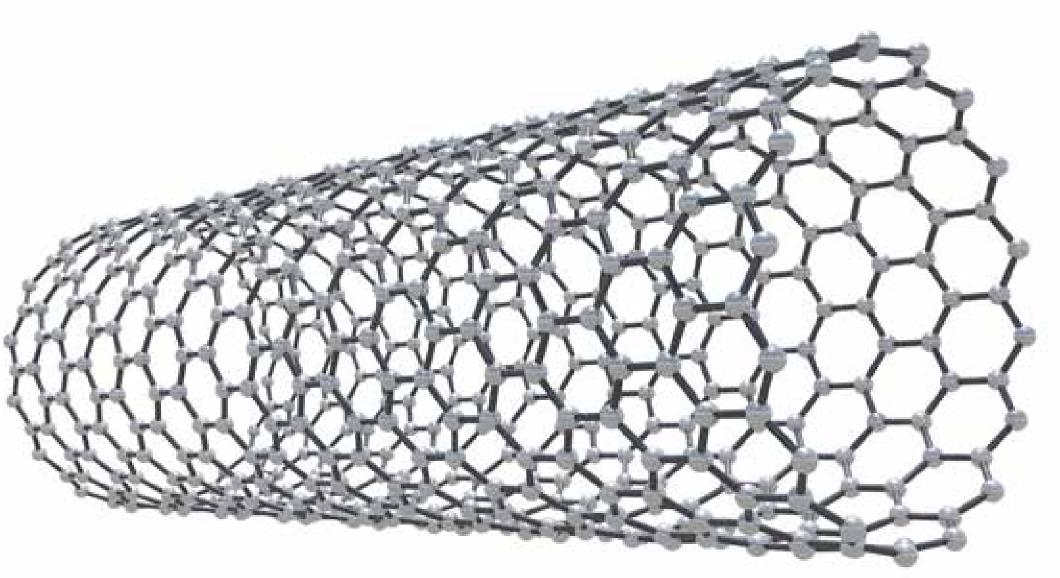



**Figure 2. Effect of compaction load vs. density on Al/0.1 CNT nanocomposite.**



***CNTs have exceptional tensile strength, low thermal expansion coefficient, and low density. Aluminum, a light metal, is being reinforced with CNT to make it even lighter and improve properties of monolithic aluminum.***

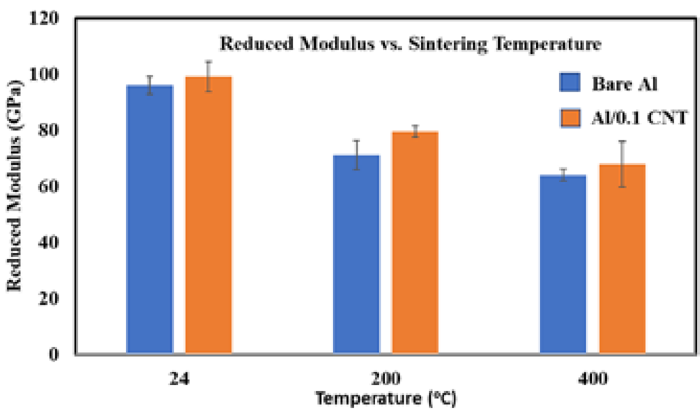



Figure 3. Reduced modulus vs. sintering temperature in bare Al and Al/0.1 CNT.

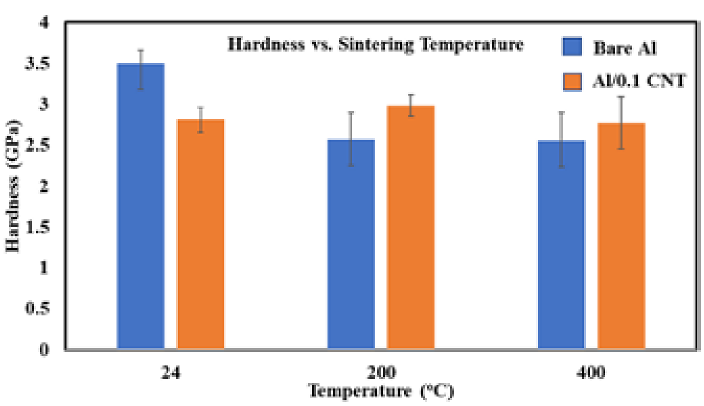



Figure 4. Nanohardness vs. sintering temperature in bare Al and Al/0.1 CNT.

were higher than that of bare Al. The 0.1% CNT reinforced matrix showed an increased thermal stability at higher temperature leading to higher nanohardness and higher reduced modulus compared to bare Al. Uniform distribution of CNT in the matrix and chemical bonding of CNT with Al that led to formation of aluminum carbide (Al4C3) nanoprecipitates boost the overall performance of MMNC. These carbides provide added thermal stability and increase strength by precipitation hardening mechanism. Though nanocomposites have higher tensile strength, they tend to have lower ductility, with a brittle-type fracture mode. Typical fracture mode in MMNCs are CNT pull out, and they fracture along carbide distribution sites.

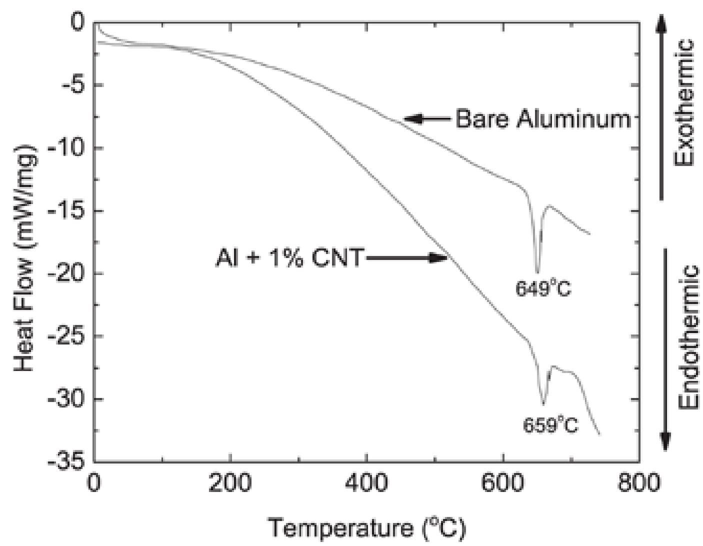



Figure 5. DSC curves of bare aluminum and Al/1.0 CNT MMNC.

Differential Scanning Calorimetric study was performed on bare aluminum powder and Al/1.0 wt.% CNT. The bare aluminum had a melting temperature of 649oC, while the Al/1.0% CNT MMNC had a melting point of 659oC, as shown in Figure 5. The shift in the DSC curve indicates an increased melting temperature of the nanocomposite. Even though both melting points are lower than the melting temperature of pure Al, a lower melting point is due to the impurities present in Al powder. The thermal property of a composite depends on existing porosity, processing temperature, fraction and distribution of reinforcement, density of the composite, and presence and distribution of nanoprecipitates.

## ABOUT THE AUTHOR


Triratna Shrestha is the manager of Metallographic Laboratory and Central Coatings Laboratory at Metcut Research Inc. He has worked with coatings for aerospace, petrochemical, and power-generation applications and has expertise in heat-treatment and creep studies of steel. He manages Central Coatings Laboratory for GE Aviation and is involved in failure analysis and continuous improvements. He received his B.S and Ph.D. in Materials Science and Engineering from the University of Idaho. He can be reached at tshrestha@metcut.com.

JACK TITUS
DIRECTOR OF PROCESS AND DEVELOPMENT ENGINEER /// AFC-HOLCROFT

*Just as with 3D printing, powder metal technology is struggling to find its way, while designers have looked for more efficient methods to produce gears and more complex shapes.*

# Thermal triplets: PM, sintering, and case hardening

From my experience, powder metals (PM), sintering, and case hardening are three processes that could be said to be joined at the hip. More often than not, the three processes will follow in succession with one interloper; debinding or dewaxing immediately following the pressing of the powder metal into a shaped form.

For the purposes of this column, I'll concentrate on liquid phase and solid-state diffusing sintering.

Although powder metals and sintering have been around for a one and one-half generations, at least from my observation they found their useful niche in small machines similar to early mechanical calculators and copiers and likely still do to a large extent. Prior to PM, plastics were extruded through dies and used to make the small gears and other drive components in the early office machines. Since these parts were so small, machining labor was just too expensive, so injection molding became the preferred manufacturing process. This process led to metal injection molding (MIM). I'll discuss this process later. Of course, some parts — even though they were very small — were required to withstand considerable wear, so machining from metal was necessary.

Over the decades engineers and manufacturing were desperate to find more uses for PM primarily due to the net shape capability they provided. However, PM has two major stumbling blocks that they continue to try and overcome:

› First, the part had to be capable of being removed from a hydraulic press, therefore any component had to be fairly simple in configuration — cylindrical or some similar shape with straight sides.

› Second, although extreme pressure is used to compress parts, 100 percent void free is impossible to achieve. Why? First, a binder is blended with the powder because without a binder/lube the compact has no strength when it's removed from the press and some strength is required for the parts to hold their shape through the handling required to transport parts between processes. Since the maximum practical sintered density can vary depending on the alloy grade and application about 85 to 92 to 98 percent the binder/lube serves two purposes. It allows the part to retain its shape and reduces the friction when extracting high density parts from the press.

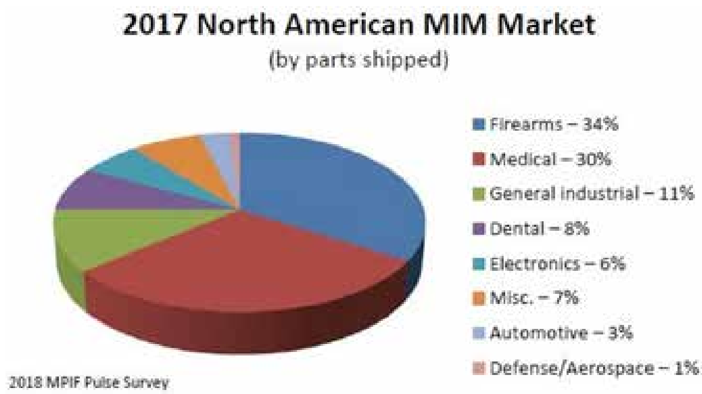
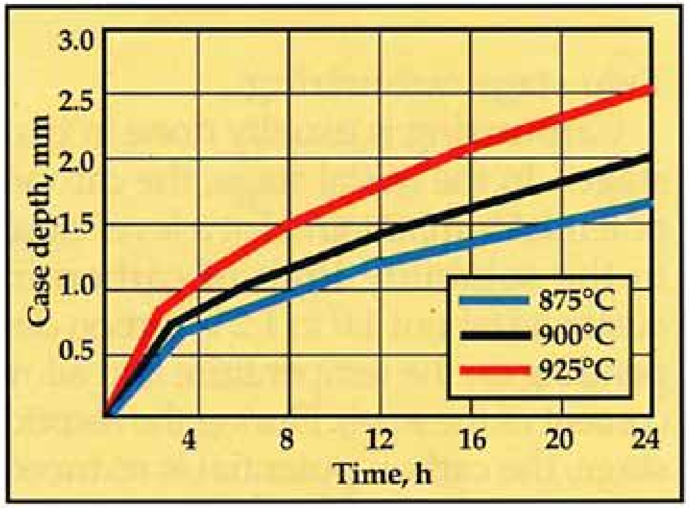



**Figure 1**

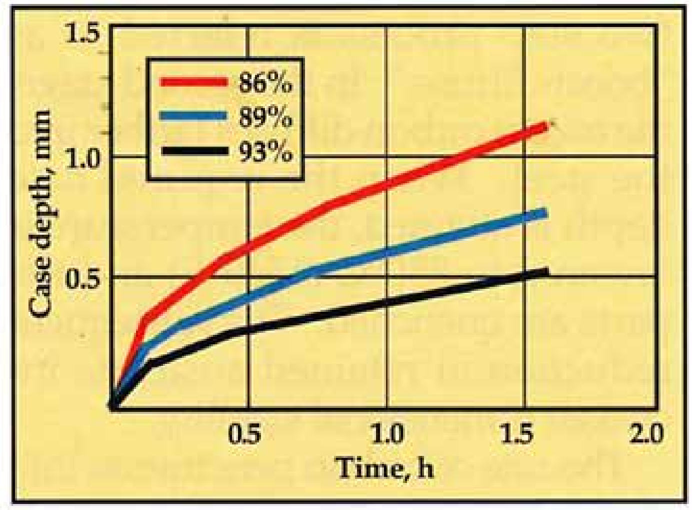
Over the years there have been attempts to improve the surface density of PM parts, especially gears (teeth) to better compete with their wrought machined counterparts. However, there are two considerations when densifying gears. First, the tooth contact area must be as close to theoretical density as possible to withstand the compression and bending forces that drive-trains, especially automotive, must endure. Second, PM parts have notorious fatigue issues due to the microscopic voids on the surface that act as stress risers in specific applications. Therefore, the densification effect must not be limited to the surface but penetrate below the tooth's pitch line into the tooth core, which is the center point between two adjacent tooth roots. This is not easily done while retaining the critical dimension of the gear specifications.

Back to MIM. Metal injection molding, as mentioned earlier, is an adopted process from plastic injection molding, but that's where the similarity ends. As designers looked for more efficient methods to produce gears and other more complex shapes than traditional PM processes could provide, some of them began experimenting with the MIM process about 40 years ago. MIM shares some similar characteristics as sinter HIPing, a process I've discussed in earlier columns.

For MIM to work, the metal powder must be much finer than that for PM and the binder/lube is quite different than traditional PM. In normal PM, after the parts are pressed all of the binder/lube or as much as possible must be removed prior to sintering. In MIM, the binders consist of two materials — one to keep the part shape from sagging since by design their shapes are more complex, and a




CASE DEPTH TIME FOR WROUGHT STEEL




CASE DEPTH TIME PM STEEL

**Figure 2**

second higher temperature binder that is removed during sintering. In fact, to enable the powder to be forced to flow into the complex die designs the binder content can be up to 45 percent by volume of the part [1], Figure 1. Due to the volume of binder required, the finished product will have shrunk in volume by up to 18 percent. Over pressure sintering or sinter HIP or tungsten or silicon carbide also produces a similar shrinkage but for different reasons.

Sinter HIP is a liquid phase sintering process where cobalt acts as the secondary binder but is not removed. Special waxes provide the primary binder to keep the part from fracturing during handling. A batch operation sinter HIP goes through two hot processes; first debinding, and then high temperature sintering in the same vessel. While at temperature with all binders removed, the parts are exposed up to 60 bar pressure of argon that compresses the parts while the cobalt becomes semi liquid to fill the remaining voids in the component and results in shrinkage.

Conventional PM sintering, including MIM, relies on a solid state or diffusion bonding between powder particles; no melting takes place. Since PM and MIM have an open pour structure, MIM shrinks due to the explanation above, whereas traditional PM parts shrink only slightly if at all. Sinter HIP parts shrink because the semi-liquid cobalt flows to close the pores thereby producing a closed pore structure — thus the argon gas does not penetrate the parts, forcing the part to compress.

Since most of the PM parts manufactured in the U. S. contain low alloy, they have little strength after sintering. Even higher alloy powders must be heat-treated to improve hardness and strength. Since the alloy content of PM is the same throughout the cross section, they typically are neutral hardened, assuming the final hardness is appropriate for the application. However, where surface hardness is critical, carburizing is still the standard for improving wear resistance, especially in drive train components. PM parts can be carburized just as any ferrous alloy — the difference is due to the open-pore structure that allows the carburizing atmosphere to penetrate significantly faster than in fully dense wrought materials [2]. (Figure 2)

Although the open pore surface structure has advantages for carburizing, its major disadvantage is quenching. The quench fluid will enter the part surface to some depth, therefore oil is the preferred fluid. Thus, only higher alloy PM parts — unless very small — can be successfully hardened. With lower alloy PM parts where wrought material can be water or polymer quenched, low alloy PM parts will likely rust if quenched in water if not immediately heated to evaporate the water, and that's still difficult in high-humidity conditions. Washing after oil quenching PM is also not advised. What's the option to remove the absorbed quench oil? Tempering is conducted in gas-fired tempers that have either nitrogen atmosphere or excess air with an after burner on the effluent to burn the vaporized oil. The result can be as follows:

› If the tempering temperature is too low, not all of the oil will vaporize and/or the final hardness would not be met unless temper time is extended.

› Tempering too high will remove most of the oil, but the hold time will have to be adjusted to obtain the proper hardness.

## REFERENCES

[1] "Powder Injection Molding International."

[2] "Carburizing P/M Parts," by Thomas R. Prucher, BurgessNorton Mfg. Co. St. Louis, Mo.

## A FAREWELL

After writing the Hot Seat column since January 2011 until today, eight years except for 2016, I feel the time has come for me to focus on other things. Although I am retired, some may say "what retirement"? Because I just can't sit still after working 58 years in the heat-treating and metallurgical industry. I never did consider myself a writer until *Gear Solutions* asked me to write a monthly column, later transitioning to *Thermal Processing*. "Hot Zone" and "Hot Seat" were the choices for the column titles, but I chose "Hot Seat" because I always wanted to find a way to bring more understanding of heat-treating and metallurgy to those who had an interest but couldn't get by all of the theory being published in the trade magazines. My goal was to make it more personal, relating my own experiences in the industry, hoping to create interest from a unique perspective not usually found in technical writing without losing the technical aspects. This June column is my last. I sincerely hope I've made heat-treating a little more understandable.

## ABOUT THE AUTHOR

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JASON SCHULZE
METALLURGICAL ENGINEER /// CONRAD KACSIK

*The process must capture all requirements needed to produce conforming product in accordance with customer requirements.*

# The importance of contract review

Within any aspect of our business structure, understanding the specific requirements needed to produce product that conforms to customer requirements is important. These requirements and the recognition that the requirements can be met are accomplished during the contract review process.

In this article, we will look at how the contract review process is typically performed, as well as different ways to perform contract review, which will minimize risk throughout a thermal process.

## THE PROCESS OF CONTRACT REVIEW

Contract review is a process in which specific product or process requirements are reviewed to ensure a supplier has the proper staff, approval, and equipment capability to produce the product or process. I will be focusing on contract review as it relates to thermal processing.

To start, it is important to document your company's capabilities. This will include all aspects of your company's thermal processing capabilities. These capabilities, including specific prime/industry certifications/approvals, will include many aspects of the process ranging from furnace-qualified operating range to testing techniques. Let's go over this a bit more in detail.

## LIMITATIONS AND REQUIREMENT DOCUMENTATION

Assuming a supplier already has a thermal process within its manufacturing or service scope, the limitations of that process must be documented. This is typically accomplished by first testing the equipment limitations. The results of the testing will give the supplier the details needed to document the limitations of the equipment within specific procedures. As an example, a supplier may test a new vacuum furnace that qualifies at 100°F to 1,600°F to +/-10°F, and from 1,601°F to 2,000°F only qualifies to +/-25°F. In this scenario, product that requires +/-10°F above 1,600°F cannot be processed in this furnace. This type of detail is important to document and be used in the contract review process. Another example could be testing performed to validate the thermal process, such as hardness testing. If a customer is being asked to perform conductivity testing, and hardness testing is the only post-thermal process testing capability in their scope, this job would not be able to be accepted.

Typically, these limitations are identified in a heat-treat/pyrometry/hardness testing procedure as applicable. They can also be assembled into a control plan or process control matrix that is usable by other departments, such as contract review and purchasing. This action enables other departments to review and have quick access to the details of the process/equipment limitations. It is good practice to limit the number of documents the capability details get placed in, as the more documents in which they are placed, the more documents that must be changed when capabilities and/or requirements change.

**The results of equipment testing will give the supplier the details needed to document the limitations within specific procedures as part of contract review. (Courtesy: Shutterstock)**

## TRAINING

Training for staff who perform contract review is just as important. Clearly, there is no need for contract review personnel to understand metallurgy and how to operate thermal-processing equipment. However, understanding the equipment and process limitations as they apply to contract review is imperative.

Training should be structured in such a way that contract review personnel not only understand where to obtain the information they need, but also what it means. If I were to tell staff in contract review who were not trained that a particular furnace is limited to a Class 2 +/-10°F, it wouldn't mean too much to them. If I were to design a focused training session for contract review personnel that discussed what furnace class is, where it comes from, how it is designated, and how it applies to the contract review process, they may think, "OK, if I receive an RFQ for a thermal process that requires 1,650°F +/-5°F, I

***Assuming a supplier already has a thermal process within its manufacturing or service scope, the limitations of that process must be documented.***

cannot accept the job without speaking to engineering/quality first." As always, the training should be documented and repeated when procedures require it.

Also, for those suppliers Nadcap accredited in heat treat, the AC7102 checklist specifically requires personnel performing contract review receive training.

## IN PRACTICE

Of course, in practice things can be more challenging. A system must be developed for personnel performing contract review that can be used in both potential new product, existing product, and existing product that has had changes made to the requirements.

I have seen several ways this process is established. Most include an appropriate contract review procedure which references a contract review form or checklist that is used by contract review staff. For suppliers with captive thermal processes, the contract review checklist may include additional items aside from thermal processing such as machining, inspection, and special process requirements. For those suppliers who provide only thermal-processing services, the checklist will be limited to the capabilities of process and test equipment. It's important not to forget industry, prime, and Nadcap certifications should also be included in the scope of capabilities. Requirements for approval may be flowed down from potential or existing customers, and contract review staff should be trained and aware of this.

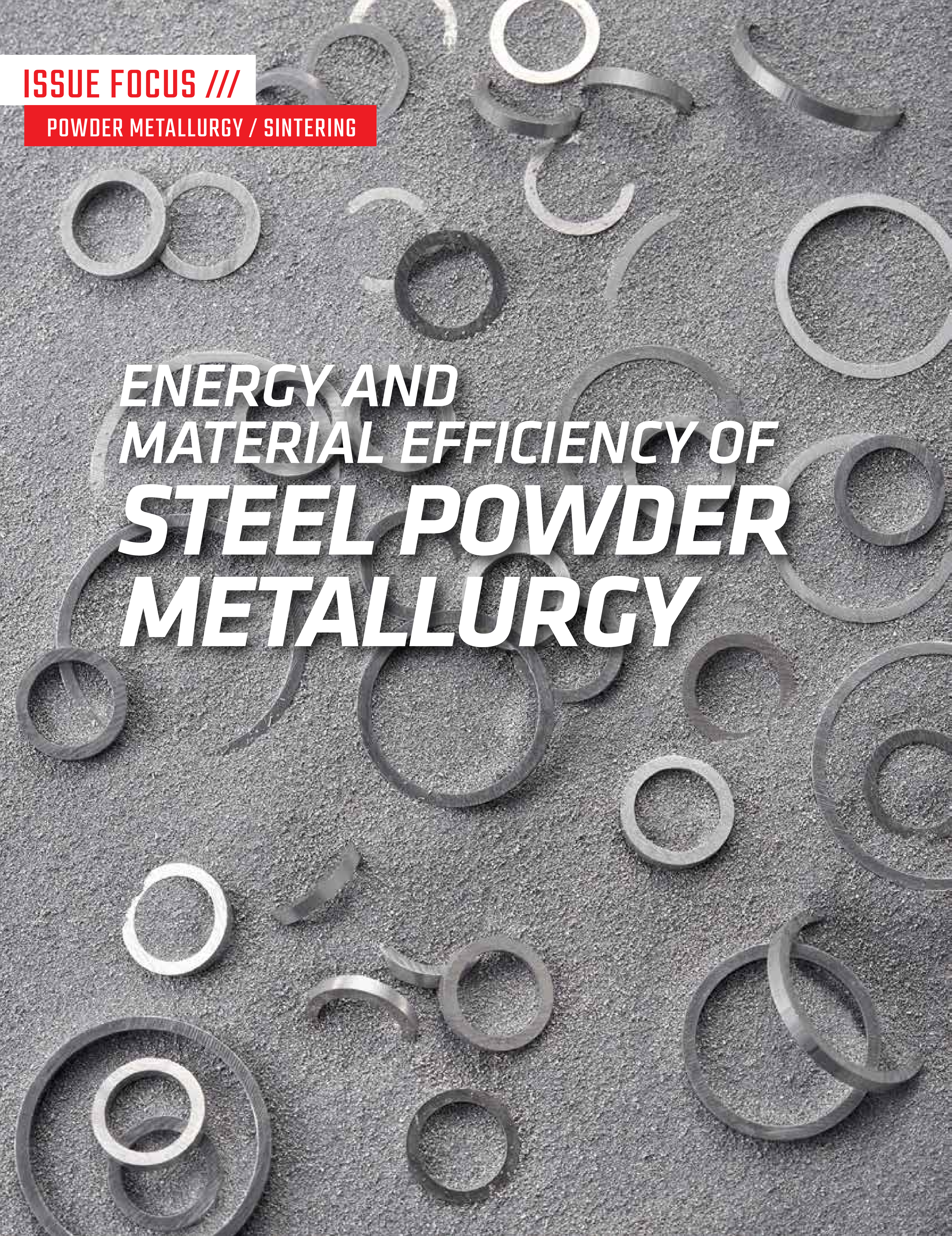
The checklist is typically used once an RFQ or purchase order is received. In some instances, the contract review checklist is routed to quality, production, and engineering for approval as each department may play a different role in the review process. This practice acts as a check and balance to ensure that a supplier has the necessary capability and approvals to process production hardware.

## SUMMARY

The contract review process can be established and practiced in a variety of ways. The key is to ensure the process captures all the requirements needed to produce conforming product in accordance with customer requirements.

### ABOUT THE AUTHOR

Jason Schulze is the director of technical services at Conrad Kacsik Instrument Systems, Inc. As a metallurgical engineer with 20-plus years in aerospace, he assists potential and existing Nadcap suppliers in conformance as well as metallurgical consulting. He is contracted by eQualearn to teach multiple PRI courses, including pyrometry, RCCA, and Checklists Review for heat treat. Contact him at jschulze@kacsik.com.



# *ENERGY AND MATERIAL EFFICIENCY OF* STEEL POWDER METALLURGY

# Powder metallurgy processes provide opportunities that are not available when using material in the conventional form: Melting is not required in order to form complex components, and the rapid solidification typical of powder production allows for use of highly alloyed compositions.

**By JOSÉ M.C. AZEVEDO, ANDRÉ CABRERA SERRENHO, and JULIAN M. ALLWOOD**

Concern about global warming motivates the reduction of greenhouse gas emissions from manufacturing, but the environmental impact of the whole powder metallurgy production chain has not been assessed yet. This paper traces the flow of energy and material through the major powder-metallurgy processes from liquid steel to final products and assesses the efficiency of both energy and material use. The results show there is significant opportunity for reducing energy and material requirements in delivering products. Specific opportunities such as avoiding lasers in additive manufacturing or minimizing heat losses in powder sintering are proposed and evaluated.

## 1. INTRODUCTION

Powder metallurgy processes provide opportunities that are not available when using material in the conventional form: Melting is not required in order to form complex components, and the rapid solidification typical of powder production allows for use of highly alloyed compositions. Concern about global warming has led to agreement on national and international targets to reduce greenhouse gas (GHG) emissions [1]. Industry is responsible for 35 percent of all energy/process emissions [2, p. 13]. Emissions from steel powder metallurgy are currently only a small portion of industrial emissions but may become more significant with the rapid growth of processes such as metal additive manufacturing. Wohlers and Associates [3, p. 123], for example, reported that material sales increased 49 percent between 2013 and 2014. This paper therefore aims to assess the total impact of production processes associated with powdered steel in order to identify opportunities for reducing the environmental impact of powder metallurgy.

Several previous studies have considered aspects of the environmental impact of steel powder processes. The energy inputs of press and sintering processes, which account for approximately 90 percent of the mass of products made with ferrous powder [4], have been quantified in detail by Bocchini [5]. By analyzing case studies, Bocchini [5] was able to propose measures such as reducing heat losses in sintering to reduce the process' environmental impact. Three decades later, Kruzhanov and Arnhold [6] evaluated the energy consumption of press and sintering combined with water atomization and assessed their efficiency. They concluded that the two processes are three times more energy intensive than their theoretical minimum. Compared to the other powder metallurgy processes, press and sintering have been well characterized regarding their energy and material efficiencies.

Additive manufacturing is the only process other than press and sintering whose environmental impact has been studied in the literature. Huang et al. [7] have considered the environmental impact of additive manufacturing within the complete lifecycle of metallic aircraft components and concluded that, if it is used to the full potential, emissions from civil aviation in the United States could be reduced by approximately 6 percent. Additive manufacturing allows for more design freedom than conventional processes, thus enabling further optimization of components. Faludi et al. [8] calculated the emissions at different stages of one particular additive manufacturing process: selective laser melting. They considered the whole production chain and verified the additive process is most energy intensive. Faludi et al. [8] proposed that GHG emissions could be reduced most effectively by using the machine at full capacity and turning it off when not in use. The environmental impact of additive manufacturing has had more attention from researchers than any other powder metallurgy process while making the powder — which is also important — has been ignored.

No previous studies consider the environmental impact of the whole powder metallurgy production chain — from powder production to final application. Furthermore, the energy and material efficiencies of processes such as hot isostatic pressing and gas atomization have not previously been quantified. However, at a larger scale, Cullen et al. [9] have mapped the flow of all steel across the whole supply chain leading to identification of a set of measures that could allow delivery of the same final services from less material production. This approach provides the inspiration for this paper, in which an assessment will be made of all the major powder metallurgy processes in order to explore whether there are equivalent measures for reducing the GHG emissions of making and using steel powder.

The methodology used to analyze the whole steel powder production chain is described in the next section. The results are shown in Section 3 and a set of actions to reduce the environmental impact of powder metallurgy processes is proposed and discussed in Section 4.

## 2. AN ANALYSIS OF THE STEEL POWDER METALLURGY PRODUCTION CHAIN

In order to develop a complete picture of the energy and material requirements of the powder metallurgy production chain, this section maps the sector and compares current practice with estimated limits to determine its efficiency. A map of the production chain is first developed in Section 2.1. The potential for improving the efficiency of energy use ( Section 2.2) and material use ( Section 2.3) is then calculated.

### *2.1 A map of the production chain*

In order to provide a holistic picture of the production of final parts from steel powder today, a map is developed to trace the flow of material and energy inputs into the required chain of processes from initial production to final application. Constructing this map requires that data from diverse sources is reconciled with estimates used to fill data gaps.

The steel powder metallurgy production chain is divided into four steps (Table 1).

Most steel powder is made from liquid steel, so the production chain starts with processes that are similar to conventional steel making. Large powder producers tend to use steel made from prompt scrap in electric arc furnaces [10], while smaller powder producers are more likely to use induction melting. Since two thirds of atomized powder is made by large producers, and the rest is made by smaller operations [11], this proportion was assumed for the distribution of electric arc and induction steelmaking. Steel must typically be refined after melting and Höganäs AB [10] describe the use of ladle refining, which was assumed to be the most significant refining method.

Liquid steel is supplied to atomization processes in step 2 to make steel powder. Most data on powder production and consolidation is published by continental trade associations. These publish yearly reports on the state of the powder metallurgy industry that are focused on water atomization and press and sintering. The most up-to-date sources are described in the supporting information. Additional sources were used for hot isostatic pressing [4] and additive manufacturing [3]. The available data tends to be separated by whether it is related to powder production or consolidation. This is convenient because it helps to define the mass flows through steps 2 and 3 and because the continental data can be added up to estimate the global picture. Steps 2 and 3 were connected by enforcing mass balance and matching the characteristics of the powder-production methods with the requirements of the consolidation processes, which can be extracted from technical literature on PM, such as German [12].

There is limited data about the final application of powder metallurgy components (step 4). Trade associations only publish data for the press and sintering process whose main applications are in the automotive sector. The flows from the remaining processes were estimated based on qualitative remarks on their main areas of application found on process specific sources (described in the supporting information).

### 2.2 Energy efficiency of powder metallurgy processes

The most common definition of energy efficiency ($h = E_{useful}/E_{in}$) is not applicable to manufacturing processes that do not have a useful energy output (which is the case for most powder metallurgy processes). A definition of efficiency needs to: (i) allow for direct comparison of different processes; (ii) represent their potential for improvement; (iii) be based on physical mechanisms. Therefore, energy efficiency (h) was defined by,

$$\eta = \frac{\mathrm{SEC_{theo}}}{\mathrm{SEC_{real}}}, \quad \text{Equation 1}$$

where $SEC = E/m$ is the specific energy consumption, $m$ is the mass output of the process and $E$ is the total energy used by the process. The subscripts "theo" and "real" distinguish the theoretical minimum energy consumption and the actual energy inputs of the process. Irreversibilities make an efficiency of 100 percent unattainable in practice, hence the potential for process improvement can only be assessed by comparing the energy efficiencies of different manufacturing methods. However, this comparison needs to consider the restrictions caused by the practical implementation of each process. For example, melting allows for the material to be densely packed whereas sintering requires the components to be spaced out. These restrictions are process dependent and can significantly reduce energy efficiency. The comparison of $SEC_{theo}$ and $SEC_{real}$ also provides guidance in the reduction of energy losses. The two measures of energy intensity are described in the following paragraphs:

Powder metallurgy processes mainly apply heat and/or work to transform the work piece into a product. $SEC_{theo}$ is obtained by using the first law of thermodynamics to obtain the energy requirements of each process. The process parameters such as temperature and pressure are obtained from the literature and are applied assuming that there are no irreversibilities.

There is $SEC_{real}$ data available in the literature for some powder metallurgy processes (Table 2). This data was used directly in Equation 1. The lowest value was chosen when processes have multiple data points because it represents the most efficient use of the process. Most existing data covers the use of irregularly shaped steel powder to make components using the press and sintering process. This is the most significant production route according to production mass. The only other process for which there is energy data is additive manufacturing. For gas atomization and hot isostatic pressing, no energy consumption data has been published, so models were developed in order to estimate their energy intensity. The values of $SEC_{real}$ were estimated by relaxing the assumption of reversible

| | STEP | DESCRIPTION |
|---|---|---|
| Raw material production | 1 | Production of the feedstock used to make steel powder (mostly liquid steel). |
| Powder production | 2 | Manufacturing methods that transform either liquid steel or ore into steel powder. |
| Powder consolidation | 3 | Production processes that use heat and pressure to form the powder into a component. |
| Final application | 4 | Industries where the PM components are used. |

**Table 1: Main steps of the powder metallurgy production chain.**

| PROCESS | $SEC_{REAL}$ [MJ/KG] | MATERIAL | REFERENCE |
|---|---|---|---|
| Additive manufacturing | 97 | 316L | [23] |
| | 112 | 316L | [24] |
| | 220 | 17-4 PH | [25] |
| Iron oxide reduction | 22.7 | Iron | [26] |
| Powder annealing | 3.6 | Iron | [26] |
| | 3.6 | Steel | [27] |
| | 5.8 | Iron | [28] |
| Pressing | 0.1 | Steel | [5] |
| | 0.1–0.5 | Iron | [26] |
| | 3.6 | Steel | [6] |
| Sintering | 2.4 | Steel | [29] |
| | 6.5 | Steel | [6] |
| | 7.1 | Steel | [30] |
| | 10.1 | Steel | [5] |
| Water atomisation | 3.6 | Steel | [30] |
| | 6.0 | Steel | [5] |
| | 11.7 | Iron | [28] |

**Table 2: Energy consumption data of powder metallurgyprocesses found in the literature.**

processes used to obtain $SEC_{theo}$. This requires the consideration of losses due to heat transfer to the environment, friction, and other losses. This procedure is summarized for each process in the next paragraphs and described in detail in the supporting information.

The hot isostatic pressing process uses high temperature and pressure simultaneously to transform powder into a solid. The heat is supplied by resistive heating, and the pressure is applied by compressing a gas that surrounds the workpiece. The theoretical minimum energy intensity is given by,

$$SEC_{theo}^{HIP} = q_M + \frac{W_C}{m_M} \quad \textbf{Equation 2}$$

where $q_M$ is the specific heat supplied to the workpiece, $m_M$ is its mass, and $W_C$ is the work required to compress the gas. The modeled energy input is given by,

$$SEC_{real}^{HIP} = q_M + \frac{1}{m_M}(W'_C + Q_G + Q_l + Q_L) \quad \textbf{Equation 3}$$

where $Q_G$ and $Q_l$ are the heat supplied to the gas and the furnace, $Q_L$, represents heat losses to the environment, and $W'_C$ represents the energy input required to compress the gas, considering irreversibilities. The main uncertainties in using this equation to predict real process energy inputs arise in estimating the energy required to compress the gas and the steady state heat losses of hot isostatic presses. This was addressed by consulting a producer of hot isostatic pressing equipment. The calculation of all the coefficients of Equation 3 is described in Section 2.2 of the supporting information.

Gas atomization uses a compressed inert gas to break up a stream of molten metal into droplets. This is caused by transfer of kinetic energy from the gas to the metal stream. The theoretical minimum energy intensity is given by,

$$SEC_{theo}^{GA} = \frac{\dot{V}_G}{\dot{m}_M} \times \rho_G \times w_G \quad \textbf{Equation 4}$$

where $V_G/m_M$ is the flow ratio of gas volume to steel mass, r$_G$ is the gas density (the gas properties are at normal temperature and pressure) and $w_G$ is the specific work required to compress the gas. The modeled energy input is given by,

$$SEC_{real}^{GA} = \frac{\dot{V}_G}{\dot{m}_M} \times \rho_G \times \frac{q_G + SEC_G}{Y_{GA}}, \quad \textbf{Equation 5}$$

where $Y_{GA}$ is the yield of gas atomization, $q_G$ is the specific heat supplied to the gas (per mass of gas) and $SEC_G$ is the specific energy consumption of gas production. The model assumes that heat, as opposed to work, was supplied to the gas because this is practiced in industry to reduce gas and energy consumption [13]. The main difficulty in using this equation to predict the energy consumption of gas atomization is in finding representative values for $V_G/m_M$. Researchers publish this data for experimental atomizers but values are not available for industrial units. This value was chosen by consulting a steel-powder producer. The full procedure used to obtain $SEC_{real}^{GA}$ is described in Section 2.1 of the supporting information.

## *2.3 Material efficiency of powder metallurgy processes*

The quantification of yield losses and thus the characterization of the material efficiency is essential to the definition of energy efficiency of the useful material output of a process. The yield losses determine how much material must be processed upstream in order to fulfil the needs of a given process. The material that leaves a manufacturing process has three possible paths: (i) it can be incorporated into the product; (ii) it can be reused or recycled; (iii) it can be "lost." Two different types of yield losses arise from paths (ii) and (iii) and are

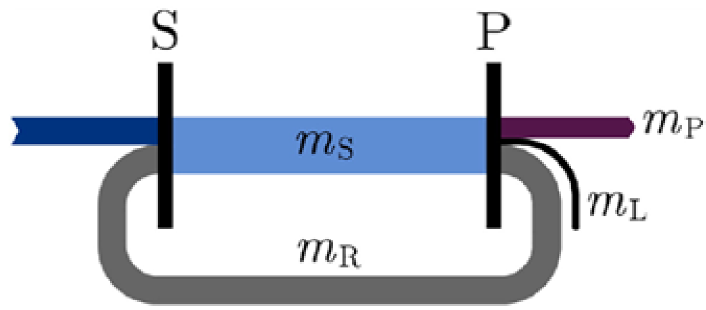



**Figure 1: Illustration of flows of material through two processes.**

| PROCESS YIELD | (YL) [%] | REFERENCE |
|---|---|---|
| Electric arc furnace | 89 | [9] |
| Ladle refining | 99 | [31] |
| Ingot casting | 98 | [9] |
| Induction melting | 99 | [32] |
| Iron oxide reduction | 92 | [5] |
| Pig iron decarburisation | 97 | [5] |
| Powder decarburisation | 98 | [5] |
| Powder forging | 86 | [33] |
| Press and Sintering | 95 | [5] |
| Metal Injection Moulding | 86 | [34] |
| Spray forming | 70 | [35] |

**Table 3: Yield values of powder metallurgy processes.**

quantified by,

$$Y_R = \frac{m_P}{\sum m_{in} - m_L} \; Y_L = \frac{\sum m_{out} - m_L}{\sum m_{out}}, \quad \textbf{Equation 6}$$

where $Y_R$ represents the material that goes through path (ii) and $Y_L$ through path (iii). $m_{in}$ and $m_{out}$ are the sum of the mass that enters and leaves the process, $m_P$ is the mass of material that is incorporated into the product and $m_L$ represents the material that is "lost." (Figure 1)

The yield values for each process were found through literature surveys (this data is summarized in Table 3). No data was found for some of the processes, so yield values were estimated using similar processes as reference (for example: water and gas atomization). Mass balances were also used to estimate yield losses when the mass flowing in or out of adjacent processes was known.

## 3. MATERIAL AND ENERGY FLOWS

Figure 2 presents a map of the powder metallurgy production chain in the form of a Sankey diagram. The material flows from left to right, from steel-making up to final application. The major input is steel scrap that is converted into liquid steel using either the electric arc furnace or induction melting. This is mostly prompt scrap. Only pig iron decarburization and iron oxide reduction use inputs other than steel scrap. Most liquid steel is converted directly into powder without intermediate casting and re-melting operations. The powder-production processes are represented toward the center of the diagram. Steel powder can be distinguished by the shape of its particles, which may be spherical or irregular. Gas atomization is the only process that makes ferrous spherical powder in significant quantities. The shape of the particles is important because the dif-

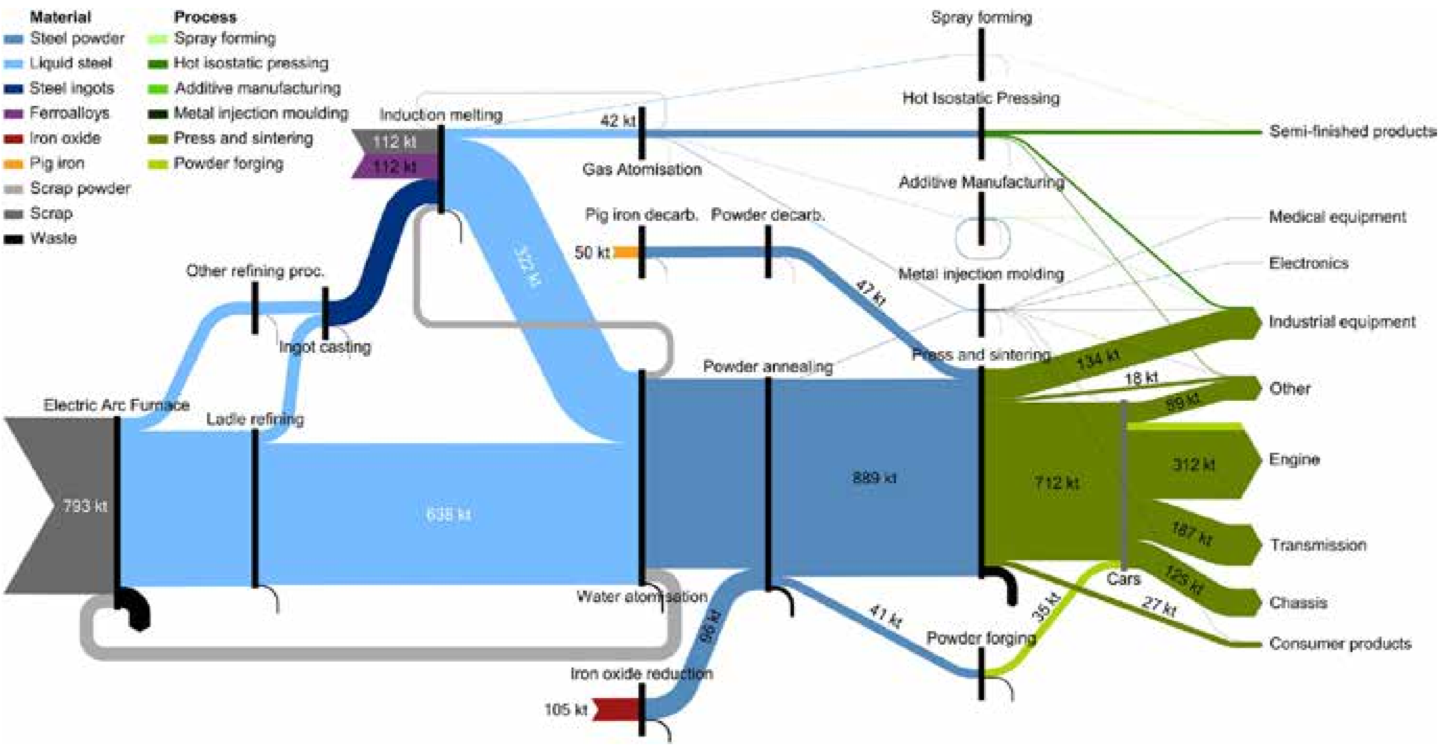



**Figure 2: Yearly global flow of ferrous powder for structural applications. Sankey diagram, the material flows from left to right and the width of the lines are proportional to the mass. Most data sources used to make the diagram are from 2010 to 2015.**

ferent consolidation processes can only work with particular shapes. These processes are represented further to the right of the diagram. Press and sintering is the most significant and only uses irregular powder. The other consolidation processes mainly use spherical powder made by gas atomization. The main applications of powder metallurgy are shown at the right of the diagram. The biggest sector is the automotive industry which mainly uses press and sintering of water-atomized powder. The other production routes mostly use spherical particles whose mass output is an order of magnitude lower than irregular powder.

The flows of spherical powder are represented in more detail in Figure 3. Hot isostatic pressing is the biggest consumer of spherical powder and mostly makes feedstock for other processes, such as bars and billets. Additive manufacturing also uses spherical powder but has only a very small production output when compared with other processes. Metal-injection molding uses a mixture of spherical and irregular particles and its production is distributed through five major applications. Even though spherical powder is used in a smaller amount than irregular, it is used in a wider range of applications.

The energy intensity data of Table 2 was applied in Figure 4 to map the energy and material flows through the production chain. This figure shows how each process contributes to the energy consumption of the production chain. Material losses are a small portion of the total production. However, there is a loop of material in additive manufacturing that is wider than its total production. This is auxiliary material used to support and extract heat away from the workpiece. The figure also shows there are three major energy inputs in the production chain: steel melting, powder annealing, and sintering. The powder annealing and sintering processes consume at least the same amount of energy as material melting. These two processes use most of the energy supplied to the production chain.

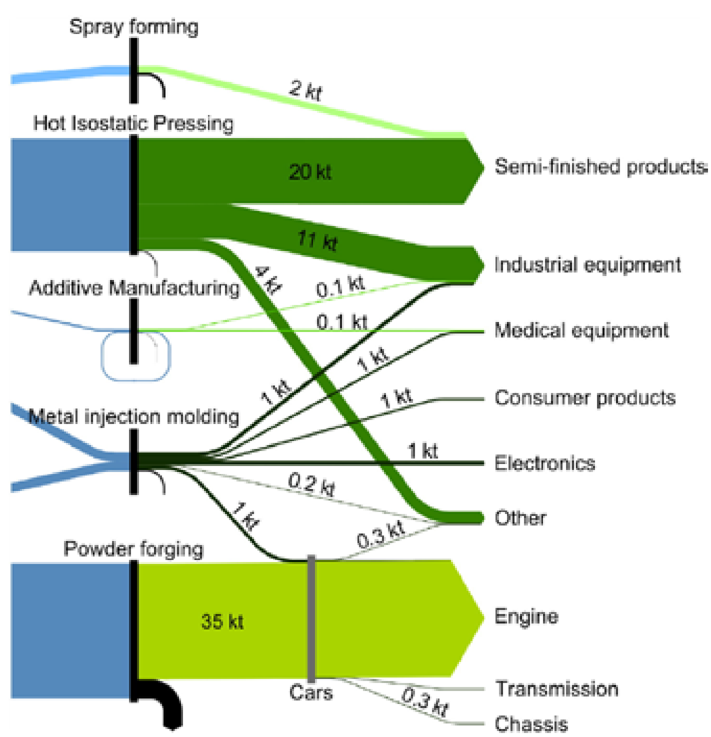



**Figure 3: Flow of material from consolidation process to final application, close up view from Figure 2 without the press and sintering process.**

## 4. OPPORTUNITIES TO REDUCE GHG EMISSIONS IN PM

This section assesses how the results of this paper can be used to reduce the energy and material inputs of the whole production chain. The following paragraphs propose and evaluate a set of measures to achieve this. The section concludes with an assessment of the main limitations of this analysis and suggestions for future work.

Most of the world's steel powder is made by water atomization, consolidated using press, and sintering, and used in the automotive sector (Figure 2). The main material input of the production chain is steel scrap, which has a much lower embodied energy than

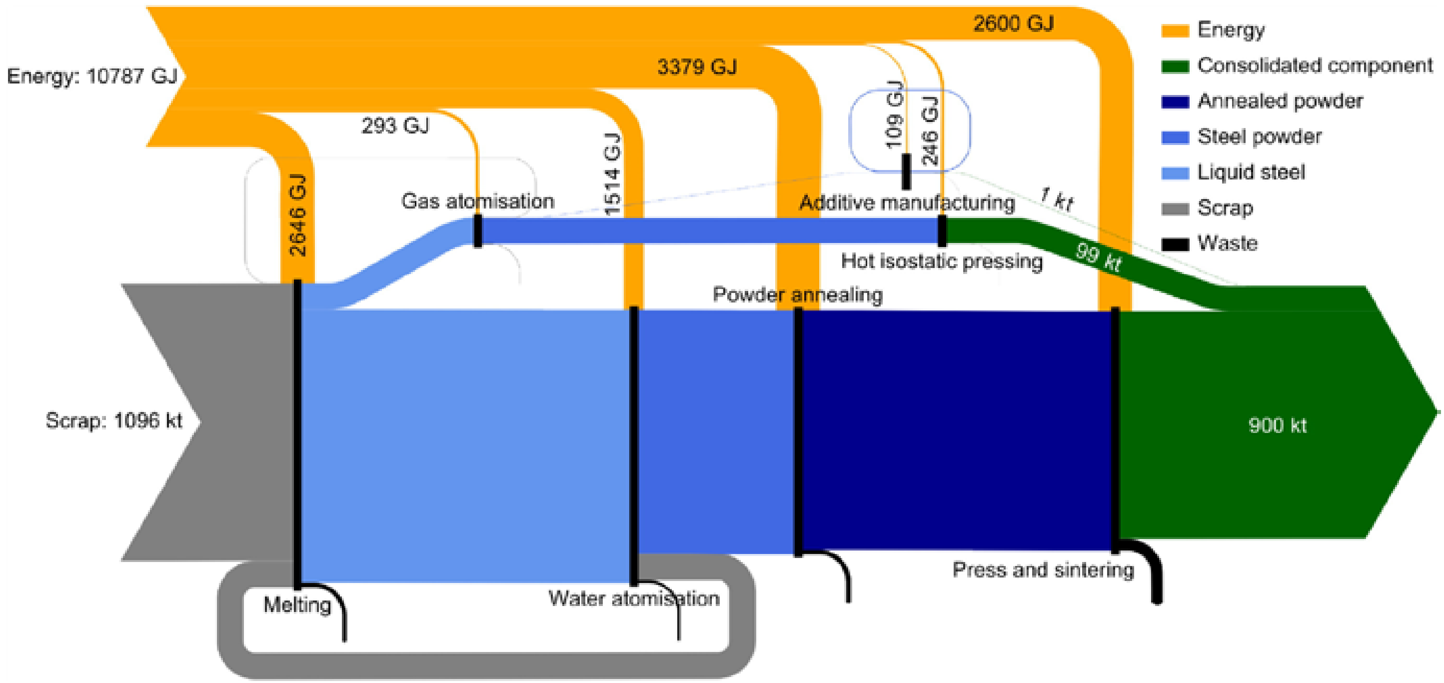



**Figure 4: Simplified flow of steel powder and energy where the proportions of mass of material are similar to Figure 2.**

| PROCESS | $SEC_{THEO}$ [MJ/KG] | $SEC_{REAL}$ [MJ/KG] | η |
|---|---|---|---|
| Induction melting | 1.3a | 2.2b | 59% |
| Gas atomisation | 0.3 | 2.7 | 11% |
| Water atomisation | 0.4c | 1.4c | 28% |
| Powder annealing | 0.5 | 3.6d | 14% |
| Sintering | 0.6 | 2.4e | 26% |
| Compaction | 0.1c | 3.6c | 2% |
| Hot isostatic pressing | 0.6 | 1.5 | 42% |
| Additive manufacturing | 1.3a | 97f | 1.3% |

References: a[36], b[37], c[6], d[27], e[29], f[23]. The unreferenced values were estimated in this work (explained in Section 2 of the supporting information).

**Table 4: Energy efficiency of the powder metallurgy processes studied in this work. References: a[36], b[37], c[6], d[27], e[29], f[23]. The unreferenced values were estimated in this work (explained in Section 2 of the supporting information).**

virgin steel. However, this is prompt scrap which does not provide the benefit of recycling material from end of life products. The biggest energy inputs in this processing route are steel melting, powder annealing and sintering. These comprise three heat cycles with temperatures near the material melting point. Powder annealing and sintering have higher energy inputs than steel melting (Figure 4) but work at lower temperatures, so they could, in theory, consume less energy. Table 4 further illustrates the two processes are less efficient than induction melting. These differences in efficiency can be attributed to the fact that sintering and powder annealing require continuous furnaces whereas melting is done with batch furnaces. Continuous furnaces allow for higher productivity but have higher heat losses. Powder annealing requires continuous furnaces to maximize the area of powder that is in contact with the reducing gases. This facilitates the diffusion of the gases into the powder to reduce their carbon content and increase their compactibility. The efficiency of sintering is limited because the components cannot be densely packed due to their low strength after compaction. Powder annealing and sintering comprise heat cycles where steel is cooled to ambient temperature from temperatures above 1,000°C. Steel powder is compacted in between these two steps. An opportunity to reduce heat losses would be to compact the powder at a higher temperature. This would require a more integrated production chain and changes in tooling material.

Apart from powder annealing and sintering, the other significant energy input in the production of automotive components is powder compaction. The powder is typically compacted using hydraulic presses. These allow for the high levels of complexity obtained from powder metallurgy. However, the high pressure provided by the hydraulic systems is only required when the maximum force in being applied to the workpiece. Most of the time the hydraulic pressure is throttled off, this reduces the efficiency of the process to about 2 percent (Table 4). This efficiency could be improved with the use of electric presses that do not need to be throttled back in the same way as hydraulic presses do.

In addition to the technical constraints mentioned above, there may be economic causes for the low efficiency of powder sintering. The cost of energy represents 6.3 percent[1] of the sales value of components made with press and sintering. Even though this is a significant portion, it is not a major component of the total sales value of components (compared with other cost components from Esper [17], such as labor and tooling). This means that most of the effort in maximizing profit in industry may have been applied to more significant contributors to the total cost as opposed to the reduction of energy consumption.

The energy and material efficiencies of gas atomization are dependent on the type of consolidation process for which powder is being atomized. Currently, this process seems to have minimal energy and material losses (Figure 4) because it is mostly making powder for hot isostatic pressing, which requires relatively large particles. The production of large particles requires less gas than smaller particles. If demand for additive manufacturing or metal injection molding increases, the resulting increase in gas atomization of smaller particles would require more energy and input mate-

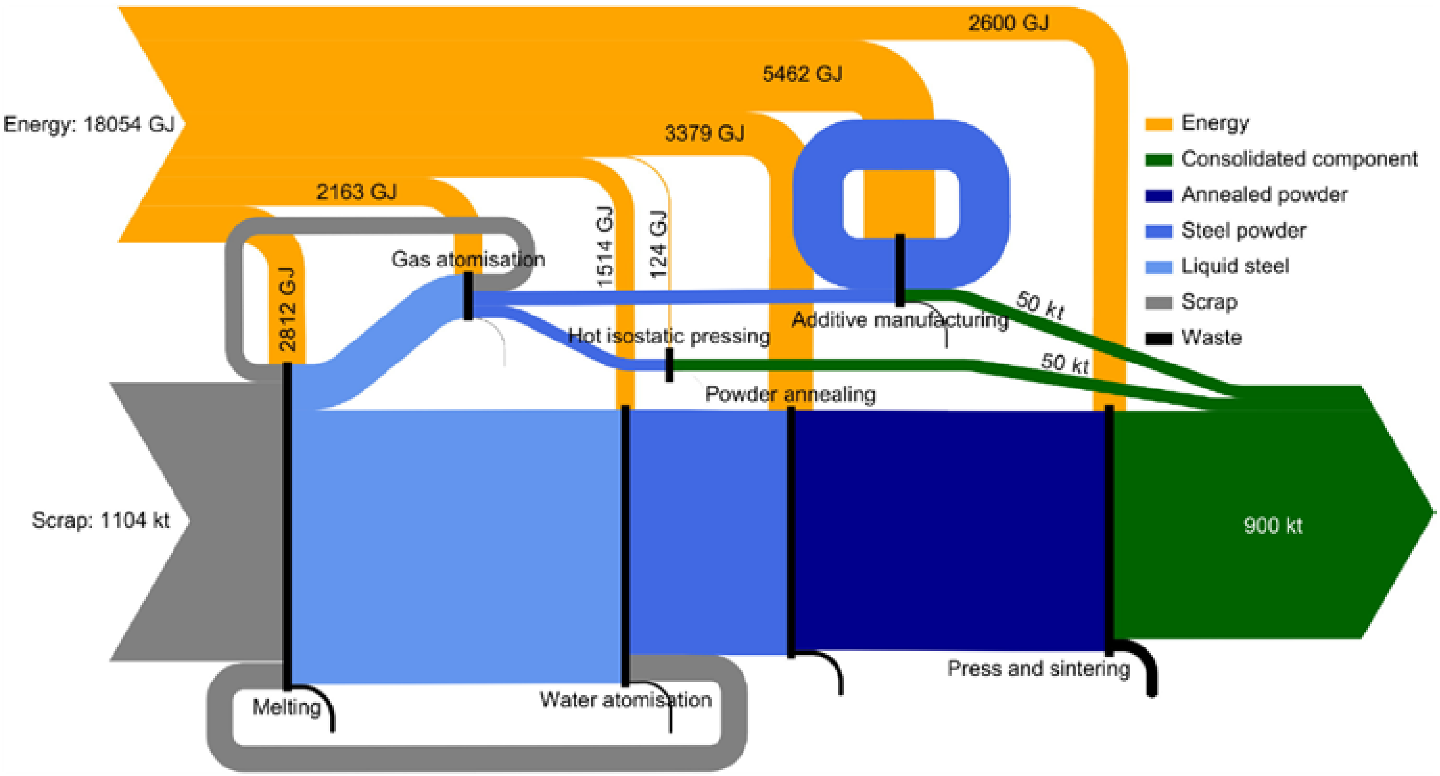



**Figure 5:. Simplified flow of steel powder and energy in a scenario where additive manufacturing produces the same mass of components as hot isostatic pressing.**

rial (this is illustrated by the contrast between Figures 4 and 5). This effect would be exacerbated by the fact that only part of each batch of atomized powder is small enough so the process yield would be reduced. The comparison of Figures 4 and 5 shows that the fraction of material sent for re-melting grows from negligible to approximately one third of the output of gas atomization. Additive manufacturing is a recent process whose feedstock requirements are not well established (as an example of this, ASTM International [18] provides standard specifications for additive manufacturing of stainless steel but does not specify which powder size ranges are acceptable). It may be possible to review the feedstock requirements to allow for more efficient use of spherical powder production.

As metal additive manufacturing is growing rapidly, a scenario where it has a significant production output is shown in Figure 5. If additive manufacturing had the same mass output as hot isostatic pressing, the energy inputs to the whole production chain could increase by 67 percent (Figures 4 and 5). Additionally, the energy inputs of gas atomization would increase by nearly an order of magnitude. Alternative atomization methods for spherical powder could be considered in conjunction with relaxing the feedstock requirements of consolidation processes. For example, centrifugal atomization, which does not require energy intensive gas, might be used to make spherical powder.

Metal additive manufacturing is still in an early stage of development with only 1.3 percent energy efficiency (Table 4), so it may not be optimized yet. As a laser is used to generate the required heat, only 9 percent of the energy supplied to the machine actually reaches the workpiece (Figure 6a). Figure 6b shows the ratio of the volume of melted material to the volume of the final component in laser powder-bed additive manufacturing, the most significant type of metal additive manufacturing according to Wohlers and Associates [3]. This ratio depends on the process parameters, but typically nearly twice the volume of the final component is melted. The use of a laser and this excess melting account for a difference factor of 20 between the theoretical minimum and the actual energy consumption of metal additive manufacturing today. Figure 6 can therefore be a driver for developing improved energy and material efficiency. For example, the inefficiencies of having a laser and material re-melting can be avoided by using the binder jetting process (this process is explained by Tang et al. [19]). Powder-bed processes have two main types of material losses: the material lost due to the powder being reused multiple times and the material required to build the supporting structures. The amount of material used in supporting structures is highly dependent on component geometry. The powder lost between reuse cycles can become significant if the mass of unused powder is higher than the mass of components. Furthermore, not all applications allow for all the powder to be reused. Material losses caused by having a powder bed can be avoided by using blown powder processes (reviewed by Thompson et al. [20]), which deposit the powder at the same time as it is being melted. These also have material losses because not all the powder reaches the melt pool, but the process only uses the material incorporated into the workpiece. These opportunities are important while additive manufacturing is still in an early stage of implementation in order to constrain the energy consumption increase that could result if demand expands significantly.

The previous discussion resulted in the definition of five measures to reduce energy and material inputs in powder metallurgy. These are summarized in Table 5. Technological changes are needed to implement them, but the previous paragraphs and Section 3 show there is significant margin for improvement. Industry practitioners have always tried to maximize their profits; this includes trying to minimize energy and material consumption. The information presented here can be used to guide them when implementing measures to further reduce emissions. The map of the powder metallurgy production chain provides a basis to evaluate these measures, and the energy efficiency data helps to quantify potential reductions.

The data used to obtain the results of Section 3 is not perfect, so there is a degree of uncertainty. The data from Figure 2 is not all from

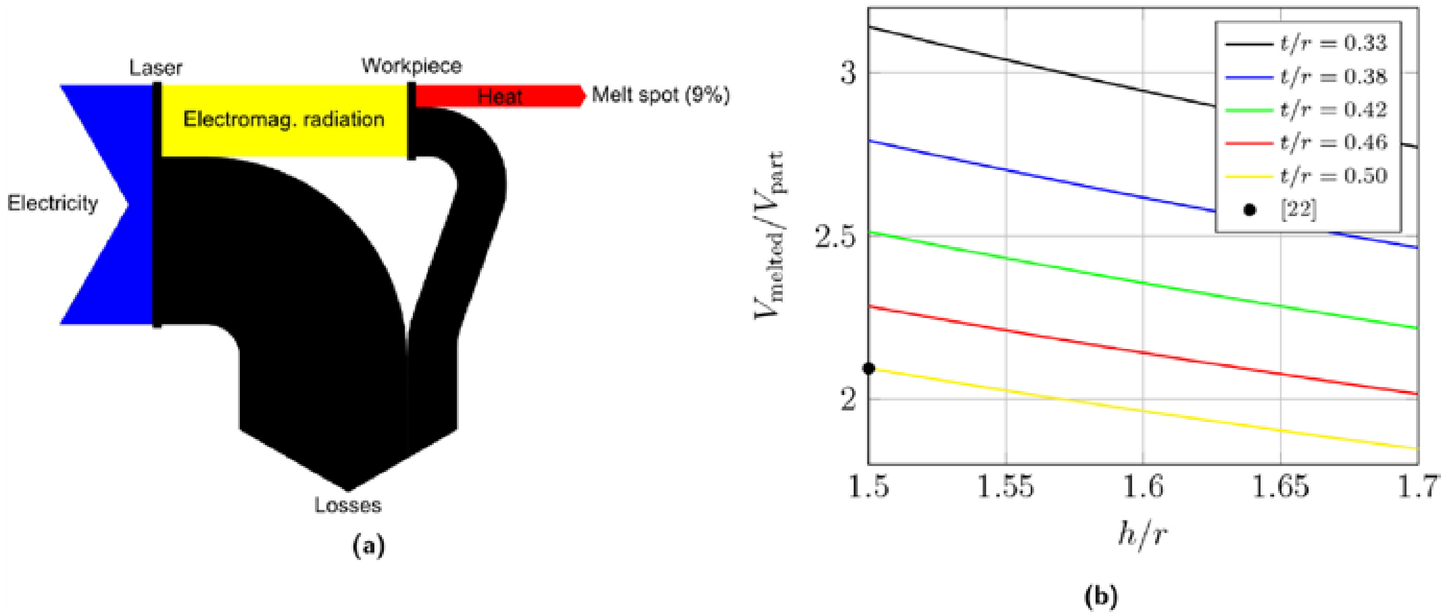



**Figure 6: Causes for low energy efficiency in additive manufacturing: (a) energy flows through a laser; (b) plot of the ratio between the volume of the material that is melted in the selective laser melting process and the volume of the component (h is the hatch spacing, t is the thickness of the layers and r is the radius of the melt pool), real process parameters from Shifeng et al. [22].**

| MEASURE | | DESCRIPTION |
|---|---|---|
| Reduce heat losses in powder annealing and sintering | 1 | These processes require temperatures lower than the melting point of the material so they theoretically require less heat than steel melting. This is not verified in practice so there is potential to increase their efficiency. |
| Relax the feedstock requirements of the consolidation processes | 2 | The yield losses and energy intensity of gas atomisation increase as the maximum allowed particle size is lowered. Finding ways for consolidation processes to tolerate higher particle sizes would result in reductions in the energy inputs of atomisation processes because less material would need to be remelted and the process would use less gas. |
| Improve single fluid metal powder production | 3 | Currently, single fluid atomisation processes do not produce a significant amount of steel powder for structural applications. These processes do not use a gas to transfer kinetic energy to the melt. It would be interesting to make single fluid atomisation processes more suitable for these applications as currently most of the energy used in powder production is supplied to the gas. |
| Do not use lasers to generate heat in additive manufacturing | 4 | Only 9% of the input energy reaches the workpiece when using a laser to generate heat. In additive manufacturing all of the volume of the workpiece is molten so a big portion of the supplied energy is lost in the laser. Alternative ways of generating heat would reduce this loss. |
| Avoid having a powder bed in additive manufacturing | 5 | The fact that powder is used to support and facilitate heat transfer out of the workpiece means that powder bed additive manufacturing processes use more material for these purposes than to make components. This is a source of material losses and alternative ways of performing these auxiliary tasks should be considered. |

**Table 5: Proposed measures to reduce energy and material consumption in powder metallurgy.**

the same year. Even though there were no major variations across different years (as described in the supporting information), assumptions were required in order to reconcile the various material flows. Energy inputs were also estimated for some processes. These values were validated by industry experts to ensure the orders of magnitude are correct. Furthermore, most of the energy intensities used in this work were obtained assuming the equipment was operating at full capacity. Kruzhanov and Arnhold [6] had access to data from real press and sintering factories and verified that energy intensity is sensitive to capacity utilization, and underutilized operations tend to consume more energy. This paper attempts to reduce energy and material consumption at an absolute level so the best-case scenario has always been used as a starting point. Due to data uncertainty and assumptions, decisions should rely only on the orders of magnitudes of flows and not on their exact values. The measures proposed in Table 5 are general and qualitative, so they are probably valid regardless of their uncertainties. There are other environmental impacts from powder metallurgy besides GHG from energy production. Two examples are the extensive use of water in water atomization or the negative effects of small particles on the human body (as reported by Brunekreef and Forsberg [21]). These effects were not considered in this work but could potentially contribute to extend the list of measures summarized in Table 5.

The work presented in this paper could be extended further to consider the use-phase and end of life of products made with powder metallurgy. This group of processes provides opportunities to produce components with improved mechanical properties and with more complex geometries. These opportunities allow for the production of more efficient products that could have a lower energy consumption in the use-phase.

## ACKNOWLEDGMENTS

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## APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at doi.org/10.1016/j.powtec.2018.01.009.

[1]Estimated according to $P = (SEC^{PS}_{\mathrm{real}} \times C_E)/C_{PS}$ = 6.3 percent, where $SEC^{PS}_{\mathrm{real}}$ is the specific energy consumption of press and sintering [14], $C_E$ is the average cost of electricity in Europe in 2015 [15] and $C_{PS}$ is the average sale value of components made in Europe with press and sintering, per kilogram, estimated from European Powder Metallurgy Association [16].

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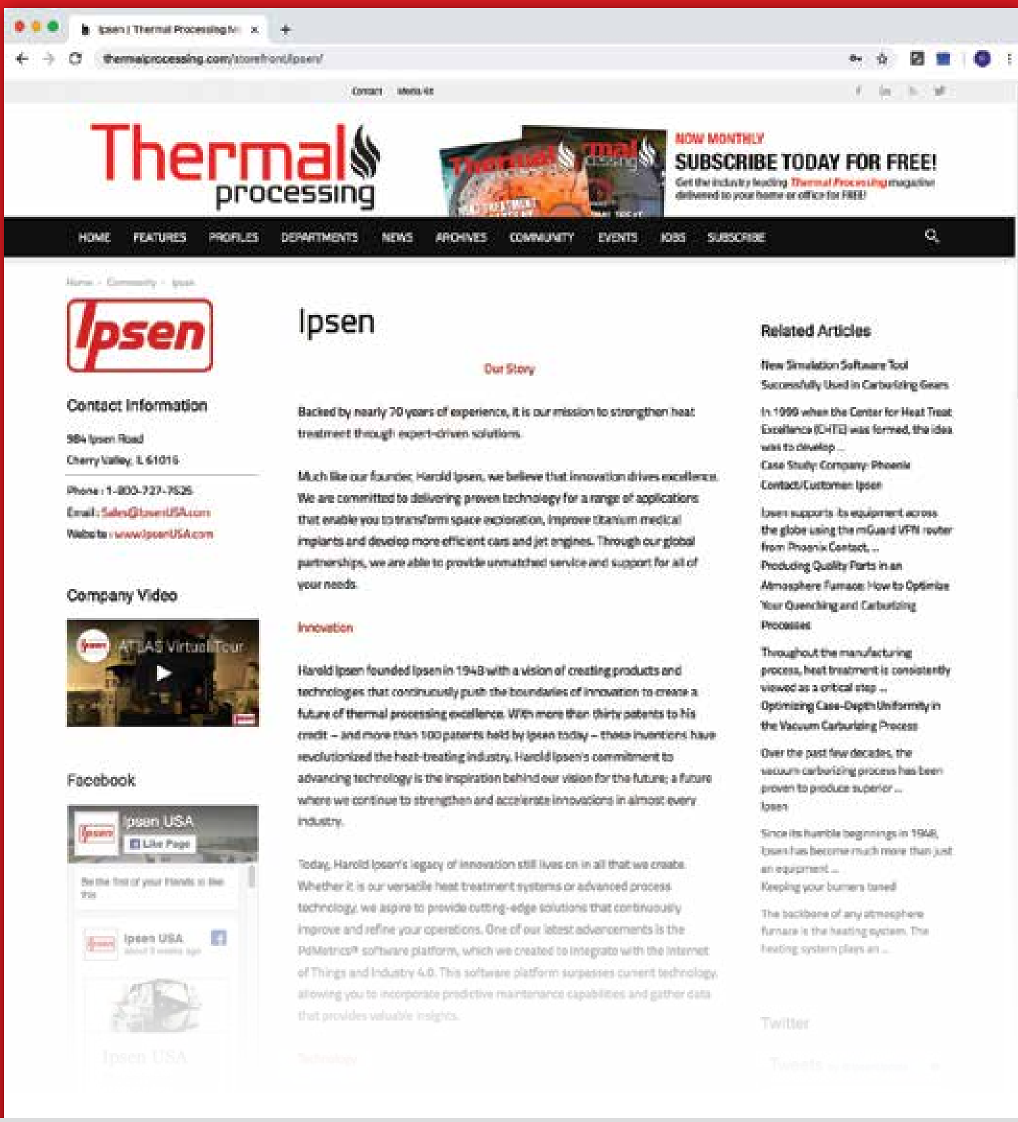


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# SINTERING EXPERIMENTS UNDER WAY ON INTERNATIONAL SPACE STATION

# Up to now, almost all sintering has been performed with gravity acting to compress the grains and make contact with the substrate. Extraterrestrial sintering experiments may determine whether more uniform sintering is possible in gravity's absence.

By RANDALL M. GERMAN, EUGENE A. OLEVSKY, ELISA TORRESANI, and DEBORAH L. HERNANDEZ

Gravity is a nonuniform stress that influences sintering densification, microstructure evolution, final properties, and dimensional uniformity. An early conjecture was that in the absence of gravity, more uniform sintering would be possible. That conjecture proved wrong. The removal of pore buoyancy, grain compression, and substrate friction results in less sintering densification and more distortion. We are finally sensing the large sintering trajectory difference associated with different gravity environments. Toward this end, parallel microgravity and ground sintering experiments are in progress. Samples in these studies are characterized for density, distortion, segregation, and microstructure. Included in the study are computer simulations of the furnace operation, sample densification, and distortion. Extraterrestrial sintering is in progress, offering time resolved densification and distortion data. Variations in sample composition allow extraction of constitutive models needed to map the sintering response with and without gravity. Such models enable predictions relevant to space-based repair and additive manufacturing. Much effort is required to ensure the experiments are safe as they are being conducted on the International Space Station, a manned habitat.

## INTRODUCTION

Extreme care is needed to ensure safety for manned extraterrestrial experiments. To that end, assessments are performed for vibration, leakage, vapor containment, toxicity, and other concerns using ground-based trials. These are performed by the National Aeronautics and Space Administration (NASA). Access to the International Space Station (ISS) is granted on a competitive basis guided by periodic NASA Research Announcements (NRA). In our case, years passed from our proposal to flight on the SpaceX CRS-14 (Commercial Resupply Service), which launched April 2, 2018.

The science is carefully assessed by independent researchers (Science Concept Review or SCR) and the hardware and assembly procedures must pass careful engineering review. These steps are over. The Low Gradient Furnace (LGF) is provided by the European Space Agency (ESA). It is located in the Materials Science Laboratory (MSL) Materials Science Research Rack (MSRR). The 12 mm diameter by 12 mm high samples are loosely packaged in 15 mm inner diameter alumina crucibles in evacuated Sample Cartridge Assembly (SCA) tubes. Science Reference Module (SRM) ground-based proof experiments are processed at the Marshall Space Flight Center (MSFC) in the Multi Use Ground Sample (MUGS) program. Trial data from Thermal Qualification Tests (TQT), and Ground Flight Tests, such as G2, are applied to make Transient Thermal Predictions (TTP) to assess actual thermal profile versus Set Point (SP) with adjustments via the Adiabatic Zone (AZ) temperature. Note that extraterrestrial research mandates learning a language of acronyms.

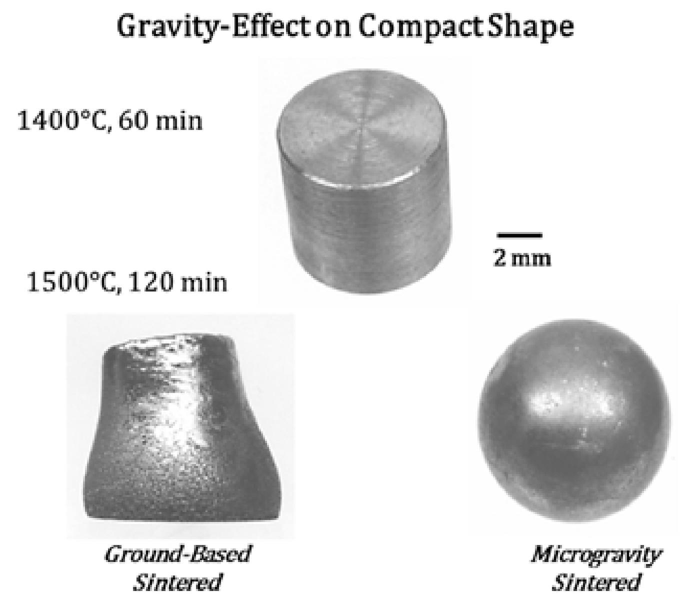


**Figure 1: Comparative pictures prior to sintering and after sintering in the same conditions with and without gravity.**

## PRIOR STUDIES

Up to now almost all sintering was performed with gravity acting to compress the grains and make contact with the substrate. For massive components, we long ago recognized gravity induced anisotropic dimensional change. Indeed, gravity is simply an accepted part of sintering.

Formal studies on anisotropic sintering response started with Lenel and co-workers [1,2] using copper compacts heated in different support orientations. Waff [3] found gradients in liquid phase sintered geological structures, including differences in crystal grain size. Subsequently, Niemi and Courtney [4] studied the gravity role in liquid phase sintering (LPS) Fe-Cu alloys with a focus on gravity induced solid-liquid segregation. In a novel variant, Fang et al. [5] relied on a neutral buoyancy system for 1g LPS coarsening experiments.

Sounding rocket trials provided first results on liquid phase sintering for 12 to 60 seconds without gravity [6]. Unfortunately, gravity effects take longer, as demonstrated by Kipphut et al. [7], Liuet al. [8], and Lame [9]. Data from microgravity sintering show a different trajectory; microgravity sintering gives incomplete densification, coalesced large residual pores, and large distortion [10-14]. An example of the sintering trajectory difference is captured in Figure 1. This image compares the pre-sintered compact (top center) with the shape after sintering at 1,500°C for 120 minutes in ground (lower left) and microgravity (lower right) conditions for 83W-12Ni-5Fe. The microgravity sample was less dense and more distorted.

With the advent of powder injection molding and additive manufacturing, anisotropic dimensional change from gravity is a problem [15,16]. Accordingly, new models arise with added gravity features [17-19]. These models are awaiting trial data from the current experiments. One long-range prospect is to use extraterrestrial additive manufacturing to construct Martian or lunar habitats. Also, additive manufacturing is anticipated for space-based repairs. These options beg the question on how to accommodate different gravitational situations, including microgravity (µg).

Earth-based sintering (1g) shows densification prior to distortion. Thus, short sintering holds are beneficial to dimensional control. Sintering in reduced gravity leads to incomplete densification since there is an absence of pore buoyancy and grain compression, while there is more distortion due to the missing stress on particle-particle contacts. If extraterrestrial habitats are to be constructed by advanced robotic factories, then problems will occur since we are unable to anticipate size, shape, density, properties, or defects when sintering in space or on the moon or Mars. These points justified the current experimental program, known as Gravitational Effects on Distortion in Sintering (GEDS). The critical questions are as follows:

**1.** How does gravity influence sintering densification and distortion?

**2.** Can this behavior be predicted?

**3.** How will this be included in computer simulations?

**4.** Will it be possible to conduct meaningful extraterrestrial sintering?

## SINTERING ON ISS

The start of this program came with the 2010 NRA and a formal bid for experiments aboard the ISS. Two years after selection, a science panel was assembled to review laboratory data in a science concept review (SCR). The research idea passed into flight qualification mode in late 2012. Subsequently, interface with the LGF required design of SCA tubes containing the samples. Several issues were addressed and difficulties overcome to allow flight hardware launch in April 2018.

The ESA provided LGF is pictured in Figure 2. It consists of a core furnace with vacuum, power, and support units for water and process gas. The left is a photograph and the right is a layout schematic. Vacuum-sealed SCA tubes containing the samples are inserted in the furnace for each run. The bore is 30 mm with 250 mm heated length; the 30 mm diameter limits sample size, the flight samples are 12 mm diameter. The furnace maximum temperature of 1,200°C as set by thermocouple life. This limitation mandated the search for a tungsten alloy that densifies at 1,200°C. The LGF has temperature stability and uniformity rated at ± 0.5°C.

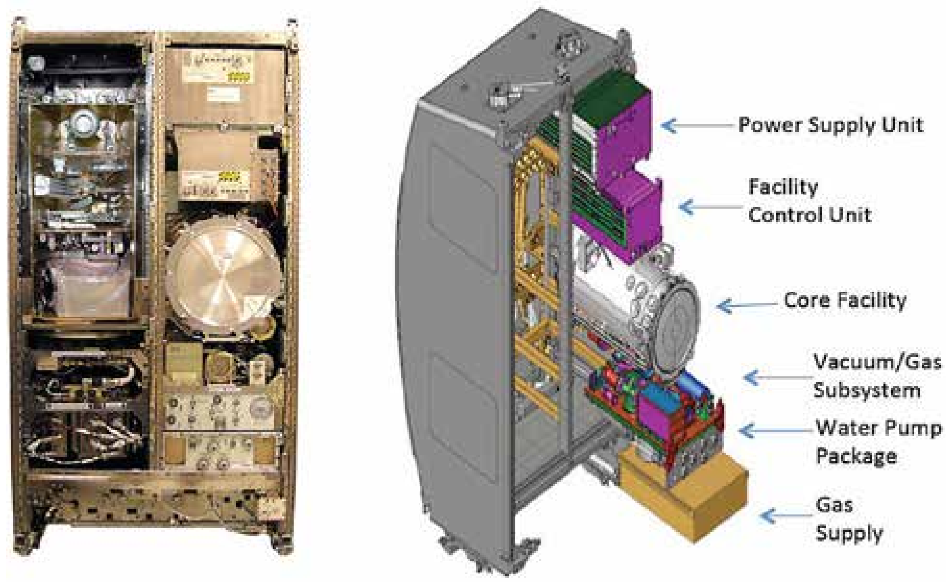


**Figure 2: Picture and schematic of the low gradient furnace (LGF) for microgravity sintering.**

| POWDER | W | Mn | N | Cu |
|---|---|---|---|---|
| Vendor | Global Tungsten | ACuPowder | ACuPowder | ACuPowder |
| Designation | deagglomerated | 301 | Type 123 | 610 |
| Particle Size, µm | 5 to 6 | < 45 | 3 to 7 | 7 to 14 |
| Pycnometer Density, g/cm3 | 19.25 | 7.21 | 8.91 | 8.96 |
| Tap Density, g/cm3 | 7.46 | 3.81 | 3.18 | 4.32 |

**Table 1: Powder Characteristics.**

## SAMPLES

The development of a W-Ni-Cu-Mn heavy alloy for low temperature liquid phase sintering is detailed in prior publications [20,21]. This alloy is compatible with the furnace temperature capability. The density difference between solid (19.2 g/cm3), liquid (10 g/cm3), and porosity (0 g/cm3) accentuates the role of gravity in small samples. Commercial tungsten, nickel, copper, and manganese powders were used as identified in Table 1.

The matrix (Ni, Cu, Mn) powders were mixed in the desired ratios, mechanically alloyed, and milled with tungsten to homogenize each composition. Logs were formed using cold isostatic pressing at 203 MPa. The logs were pre-sintered for 60 minutes (with heating hold of 60 minutes at 900°C) at 1,050°C in hydrogen, giving 63 percent density. The logs were then machined into 12 mm diameter by 12 mm high right circular cylinders with typically 13 g mass at an average 9.8 g/cm3 density. Each sample was cleaned (ethanol), dried, measured for height, diameter at four 45° rotation locations, mass, and vacuum desiccated. A 70W sample (70 wt. % tungsten) is shown in Figure 3, with the “top” registration notch evident.

Laboratory sintering trials show solid migration to the bottom, liquid migration to the top, and considerable pore annihilation. In microgravity, we expect difficulty with densification due to pore coalescence and the absence of pore buoyancy forces. Also, in µg the solid skeleton has less structural rigidity since the solid grains have reduced interparticle compression. The nominal sintering force from surface energy and feature size is 2.2 MPa acting to pull the particles together. Along the vertical axis, the 12 mm sample height at nominally 9.8 g/cm$^3$ density contributes stress at the particle contacts due to gravity in the form of an interparticle compression stress C defined as follows:

$$\sigma_C = 9.8\,(12\,10^{-3})(9800)\left(\frac{D}{X}\right)^2$$

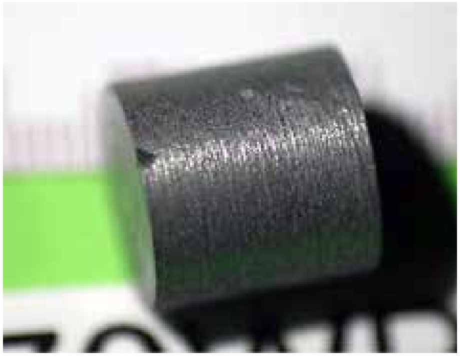

Figure 3: Machined sample.

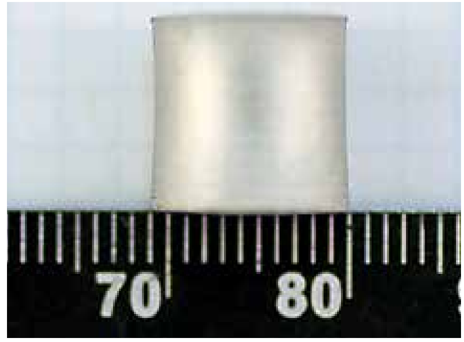


Figure 4: An example of the slightly distorted W-Ni-Cu-Mn heavy alloy after 1g sintering.

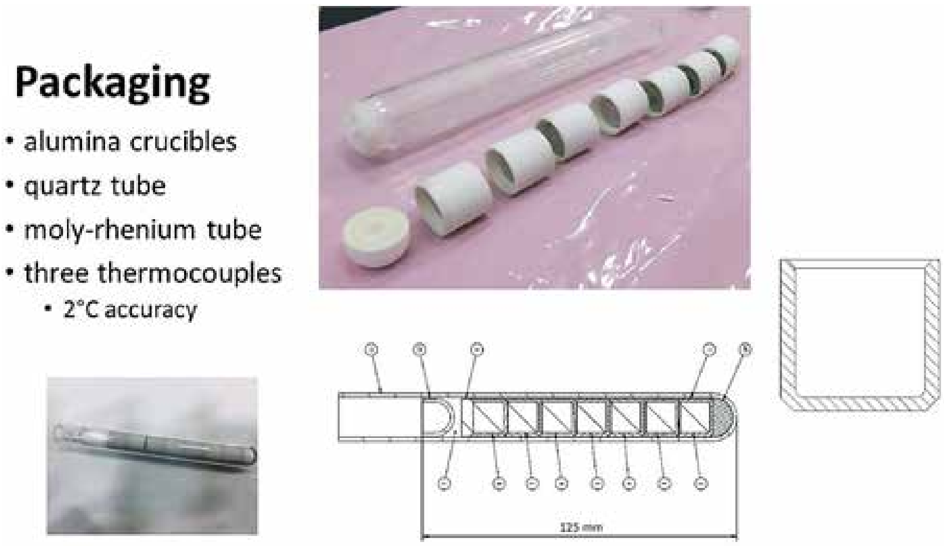


Figure 5: Stacked crucibles contain the individual samples; the images show one stack after sintering, a cross section of the stack, a cross section of the alumina crucible, and the crucible stack prior to assembly.

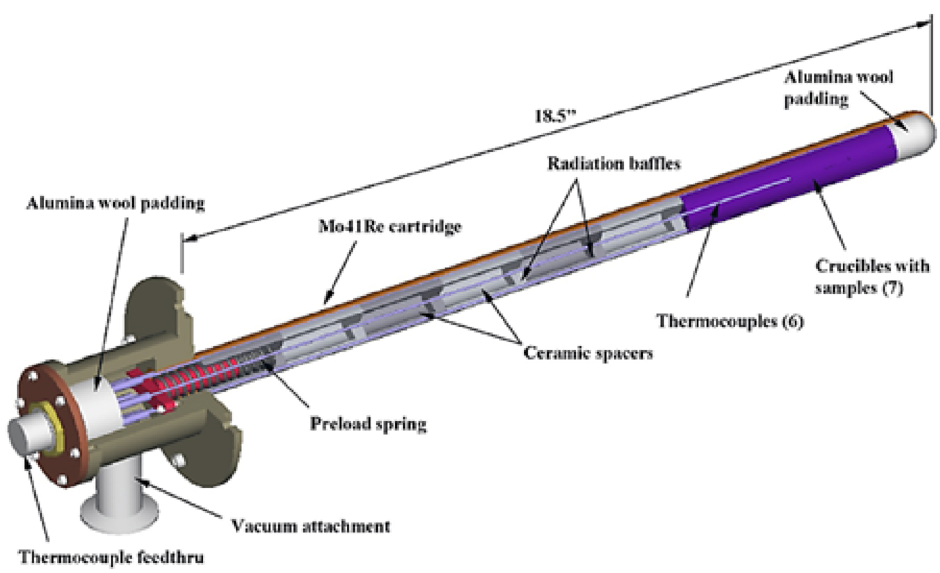


Figure 6: Layout of the insertion cartridge containing seven samples at the right end.

where D is the particle size (5 μm) and X is the interparticle-bond diameter. Setting the gravity-induced compression stress to the 2.2 MPa sintering stress shows gravity is a significant additional stress acting on the particle contacts that are oriented perpendicular to the gravitation vector. As the interparticle bonds grow, the enlargement of X reduces the compressive stress. As an example, solving for when the gravity compressive stress is the same as the sintering stress, by letting C = 2.2 MPa, results in D/X = 44. For a 5 μm powder this corresponds to X = 0.11 μm. In other words, significantly more sintering and early-particle bonding is expected in the presence of gravity, leading to more structural rigidity to resist distortion while contributing pore buoyancy to eliminate porosity. When gravity is missing, there still is a sintering stress due to capillarity. But the loss of compressive stress on the structure reduces the strong solid-solid bonds that help resist distortion. As another factor, we conjecture the degree of distortion should vary with the dihedral angle. Thus, the design of experiments includes this factor.

Thus, the design of experiments relies on changing the tungsten content to control the solid:liquid ratio at the sintering temperature (roughly the wt. % matrix times 2 gives the vol. % liquid; 30 wt. % results in 50 to 56 vol. % matrix). The alloys range from 70 to 90 wt. % W. The Ni:Cu ratio is adjusted to change the dihedral angle (measured to change from 28° to 41°). Six hold times are employed to capture the sintering evolution. In dilatometry trials and laboratory batch trials, sintering for 1,200°C took the high liquid content (70 and 80 wt. % W) alloys to essentially full density in 60 min of vacuum sintering. Short microgravity experiments are not useful in isolating the gravity effect since the viscosity of the tungsten alloys varies during densification, dropping to about 109 to 1,010 Pa·s [22]. A distorted ground-based sample is shown in Figure 4 after heating to 1,200°C for 60 min in vacuum. The anisotropic shrinkage is largely due to gravity accumulation that induced restrictive shrinkage due to substrate friction. Earlier finite element models were successful in explaining this final shape, but now the challenge is to include variable gravity levels [23-26].

The test matrix consists of 70, 80, 85, and 90 wt. % tungsten samples and three matrix composition ratios where Ni:Cu:Mn is 1.2:0.8:1 (L for low Cu), 1:1:1 (B for base composition), or 0.8:1.2:1 (H for high Cu). The Mn lowers the sintering temperature while the Ni:Cu ratio adjusts the dihedral angle nominally from 28 to 41°. Tungsten is more soluble in nickel-rich liquids, so the high-nickel content will allow more grain boundary wetting, and the low nickel content then gives different grain boundary wetting. Cartridge C0 is designed to reach the temperature (about 1,180°C), where dilatometry first indicates densification. This will document the sample condition prior to significant densification. Cartridges C1 to C6 provide time increments near 1,200°C to nominally capture the sintering trajectory up to an hour. Actual times are calculated using finite elemental thermal analysis pegged to ground sintering trials.

Figure 7: Assembled cartridge.

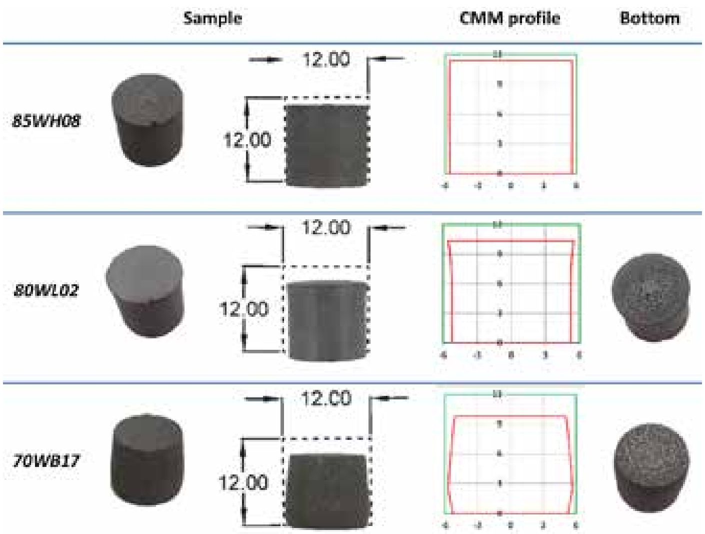


Figure 8: Images and profiles of some 1g samples used to test hardware and flight readiness. The samples have a tiny notch on the top surface to identify orientation with respect to gravity.

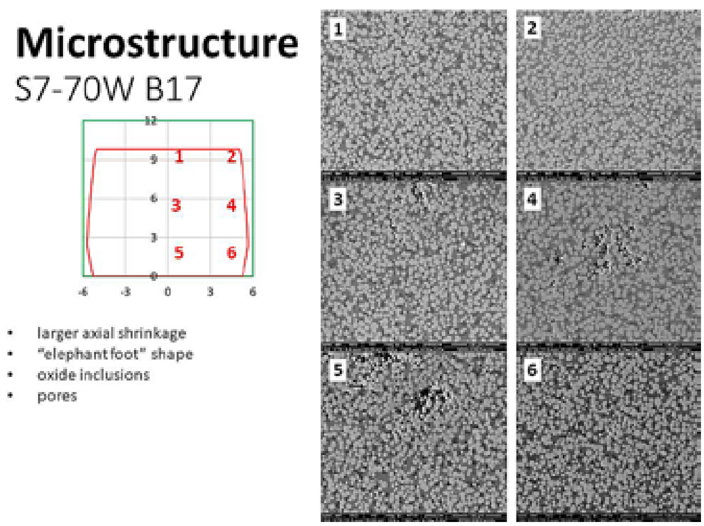


Figure 9: Trace of the green and sintered profiles and six images taken after sintering.

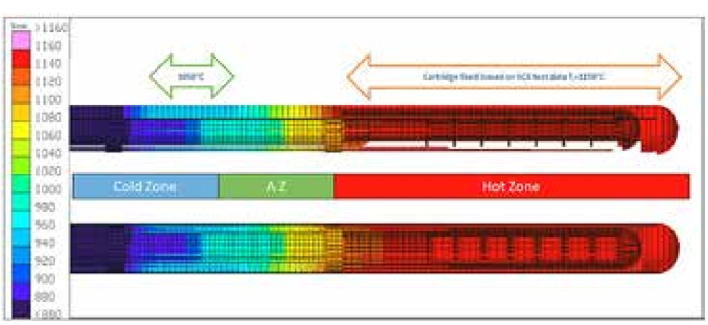


Figure 10: Example results for thermal profiles along the cartridges.

## HARDWARE

The samples are isolated in pure alumina crucibles that allow stacking, with seven samples per assembly. Similar ideas proved successful in prior microgravity experiments. Each crucible is oversized to allow free motion (expansion due to swelling and contraction due to shrinkage) during the flight. Unfortunately, early microgravity experiments only anticipated shrinkage, so crucible contact restricted distortion.

The stack is loaded into a quartz tube, vacuum outgasses, and sealed under vacuum. A fibrous ceramic packing is used to provide a cushion for expansion and contraction. The stacking idea is evident in Figure 5. This assembly is inserted into a molybdenum - 41% rhenium plasma sprayed sleeve over a zirconium boride lined alumina mandrel. Each cartridge assembly has three type N thermocouples accurate to ±2°C.

A layout of the assembly is given in Figure 6.

A photograph of the assembled cartridge is given in Figure 7. The overall length is planned to be 575 mm.

## GROUND PROOF

Trials were conducted to prove out the hardware, cartridge integrity, and experiment design. An early problem in 1g was sample sticking to the crucible, largely cured by more care in sample placement and cartridge handling. Some early quartz containers ruptured, and this was cured by adding fibrous ceramic packing in at the end of the sample stack. Instrumentation provided data for thermal analysis, and that identified a role of the adiabatic zone temperature on the temperature profile in the crucible stack. Off-gassing was a concern, as cartridge gas emission peaked just as the sintering temperature was reached. Since much of the cartridge is not involved in sample containment, the decision was to lower the adiabatic zone temperature to 1,050°C to reduce gas loads. Finally, oxidation of the manganese is a remaining concern, where the oxygen is transferred from the tungsten to manganese, since this is a volatile oxide. Thus, the hydrogen treatment used in sample fabrication.

Samples from 1g trials were analyzed for density, distortion, and microstructure. Dimensions are captured using a touch probe coordinate measuring machine. Figure 8 shows the sintered samples, and traces the starting 12 mm by 12 mm size and the sintered size. The top example is 85 wt. % W (85W), next is 80W, and the bottom is 70W. The rest of the sample designation identifies the ratio of matrix (L, B, or H as mentioned earlier) and the sequential identifier number of the approximately 20 replica samples. The selection of samples for flight versus ground was largely random. During test development, secondary quality samples were used to help understand the thermal load and to cure experimental difficulties. Various parameters are calculated to summarize the findings. For example, distortion is calculated from the nonuniform final dimensions.

Segregation of solid is detected in the microstructures. For example, the 80W composition had a 0.956 ratio of tungsten at the top versus the bottom (bottom had more tungsten as expected), indicating settling of the dense grains along the gravitational vector. The higher liquid contents distorted more, and the classic elephant foot shape was noted. The progressive increase in compressive stress with position from the sample top caused spreading of the body, but friction with the substrate resisted spreading at the bottom. Figure 9 provides micrographs and dimensional traces for a 70W sample. The micrograph locations are marked by the red numbers on the sintered profile.

The real payoff comes when microgravity sintered samples are returned for comparison.

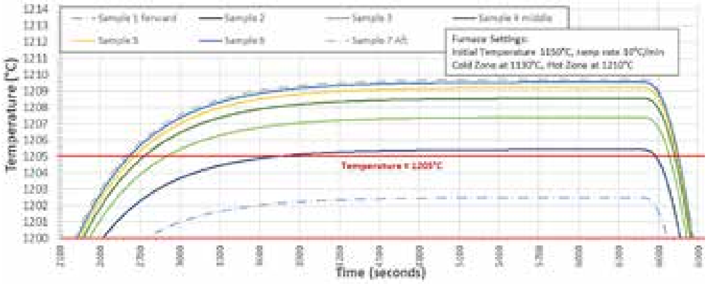


**Figure 11: Temperature versus time plot for each sample during a long duration hold, showing at set temperature of 1,205°C, showing how the individual samples reach different peak temperatures for different hold times.**

| CARTRIDGE | TIME, MIN | TEMPERATURE, °C |
|---|---|---|
| C0 | 5.6 | 1175 |
| C1 | 3.4 | 1205 |
| C2 | 6.4 | 1205 |
| C3 | 13.8 | 1205 |
| C4 | 29.1 | 1205 |
| C5 | 63.1 | 1205 |
| C6 | 6.4 | 1205 |

**Table 2: Nominal time-temperature cycles for Sample 3 in the planned heating.**

## SIMULATIONS

Finite element analysis for temperature versus time and position is employed to ensure the experiments match the desired science parameters. This requires detailed analysis of dimensions and materials so that relevant thermal attributes were included. Material properties include cartridge, thermocouple, ampoule, crucible, and sample properties of emissivity, opacity, conductivity, density, and specific heat.

Adjustments made to the adiabatic cold zone help adjust sample thermal profiles. Various heating and hold cycles enable calculation of the thermal history for each sample in each cartridge. Calibration of the model relies on test data taken during the ground based MUGS trials. The type of thermal profile simulated is illustrated in Figure 10.

Test data and simulation predictions compare favorably. In the hot zone the finite element analysis proved as accurate as the thermocouple capability. An example of the plots of heating versus position and time are given in Figure 11. On this basis, final decisions were made on the heating cycles.

Nominally, the thermal cycle results are summarized in Table 2 below benchmarked to Sample 3 in the stack. In each cartridge the peak temperature and exposure time varies with position. Note the intent is to capture sintering from the onset C0 in logarithmically spaced time intervals to 60 min C5, with C6 being a spare that can be used as a replica run for C2.

## FLIGHT DETAILS

The rare opportunity to perform microgravity sintering is a reality. The samples are fabricated, packaged, and the flight cartridges are on the ISS (International Space Station). It is a long process to reach this status, and one that requires diligence and a tremendous support team. The first cartridges on SpaceX CRS-14 (Commercial Resupply Service) launched April 2, 2018, as part of the nearly three-

**Figure 12: NASA supplied image of the microgravity conditions on the International Space Station where the extraterrestrial sintering experiments are being conducted.**

ton payload. The second launch is on SpaceX CRS-15.

Return of all sintered cartridges from ISS was targeted by December 2018. During the mission, payload specialists, such as shown in Figure 12, inserted and swapped out the cartridges, placing the sealed samples in padded suitcases for return to Earth. There was no measurement burden on the crew.

The project ends in December 2019. The research team has much analysis and modeling to perform when the samples are returned. There is nothing routine about extraterrestrial sintering, so we can only anticipate more surprises. Conceptualizations of extraterrestrial sintering using lunar or Martian resources are important to realize if exploration is to advance, and one must realize the current experiments are baby steps toward the eventual launch of robots for sintering materials harvested off-world [27].


## ACKNOWLEDGEMENTS

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# USING ADVANCED MATERIALS TO SOLVE DIFFICULT PROBLEMS

Morgan Advanced Materials' principle product range involves insulating fibers and electrical carbon systems. (Photos courtesy: Morgan Advanced Materials)

# Global engineering company Morgan Advanced Materials applies world-class material science and manufacturing expertise to solve its customers' technical challenges.

**By KENNETH CARTER, Thermal Processing editor**

A plethora of expertise makes up the complex products and services offered by Morgan Advanced Materials, but it essentially boils down to a simple concept: helping its customers achieve more with less.

However, when you look at the vast amount of what customers can get through Morgan Advanced Materials, the bottom line might almost seem like a paradox.

"From an external perspective, we would be viewed as a world leader in advanced material science and engineering of ceramics, carbon, and composite materials," said Holly Hulse, president of the Thermal Products Division at Morgan. "We operate in a number of well-defined markets, and our applications expertise offers customers a valuable differentiator. We bring highly-engineered specified materials, components, and sub-assembly parts, so that when our customers have a challenging technical problem, we work with them to solve it with our engineering combined with our materials."

**Morgan introduced Superwool® low biopersistent fiber technology in the 1990s, and the company recently introduced Superwool XTRA® fiber, the latest in this family, a breakthrough technology as this particular material has no crystalline silica formation.**

## PRODUCT RANGE

Morgan's principle product range involves insulating fibers and electrical carbon systems, according to Hulse.

"We have businesses all about seals and bearings, ceramic cores, and — back to our roots — the crucibles for metal processing," she said. "We also do a number of different customized materials that are application specific. When a customer has a specific need, we can go to them with a kind of bespoke solution."

Morgan offers its products and services to a range of industries: healthcare, petro-chemical, transportation, electronics, energy, security, and other industrial industries, according to Hulse.

"I think one of the unique things for us is that a lot of our products are required to perform critical duties in a very harsh or demanding operating environments," she said.

And a part of what Morgan does involves its Thermal Products Division, which is made up of two businesses.

"One of them is the Thermal Ceramics business, and the other is the Molten Metal Systems business," Hulse said. "On the other side of the house, we have our Carbon and Technical Ceramics division, which has three parts; Electrical Carbon, Seals and Bearings, and a Technical Ceramics business."

## THERMAL CERAMICS

Morgan's Thermal Products Division targets thermal ceramics in particular, according to Hulse.

"In this business, we're manufacturing an extensive range of high-temperature insulation products and systems that provide thermal insulation in high-temperature environments, sometimes corrosive environments," she said. "Our primary focus is high-temperature insulation and the products within that, which include insulating fiber, fire-brick, and monolithic products. And the reason that people use our products is that we help them to reduce the energy consumption in their processes."

Hulse noted Morgan's products are well known for helping customers that have high-energy processes in order to reduce energy consumption, emissions, and operating costs.

"When we come in, the value proposition we have is much more than just an individual product," she said. "We're working with them on a solution to help them solve their operating challenges and to run more efficiently."

## GLOBAL FOOTPRINT

To be able to meet all the challenges customers present, Thermal Ceramics has 36 manufacturing sites across five continents where it makes insulating fiber, fire brick, and a range of microporous products — thinner, lightweight solutions used in specialty applications in aerospace, for example.

"In aerospace, insulating fiber products tend to be a little bulkier," Hulse said. "The microporous products are condensed and, as a result, bring you very high performance but with minimal real estate."

Microporous products are perfect for performance-critical applications where insulation space is at a premium and overall weight must be minimized, according to Hulse.

"They provide a tremendous benefit," she said.

## MICROPOROUS HEAT-TREAT APPLICATIONS

Microporous products also are extremely beneficial in heat-treat applications as well, according to Hulse.

"If you think about a furnace, they can often be used as a backup insulation," she said. "Instead of having a thick backup insulation and reducing the total capacity of the kiln, by putting in a very thin layer of the microporous material, you can get some of the same benefits but in a smaller space, so you have more room to move your products."

**Morgan Advanced Materials backs up the promise of guaranteeing a solution with 163 years of experience.**

## PROTECTING THE ENVIRONMENT

Thermal Ceramics' range of products is designed to be environmentally conscious, according to Hulse.

"Morgan is focused on environmental health and safety, and we believe that flows into the products we have," she said. "When we look at the cost of energy increasing and we also see that there are more and more people focused on environmental concerns, we believe that the products we bring will allow our customers to run their plants in a more environmentally friendly way. We are looking to bring new and innovative alternative products, and we have been the leader in introducing low biopersistent products over the years to try to stay ahead of the needs — and the market — as the regulations continuously tighten."

An example of that falls a bit outside the realm of heat treatment and with Morgan's work with catalytic converters in vehicles.

"We have a number of different products that are used in holding in the heat, reducing the space, etc., to meet increasing emissions legislation, and in the heat-treatment arena, with increasing pressure on carbon dioxide and sulfur dioxide emissions, we can play a key role with our customers in enabling that," Hulse said.

## WORLDWIDE EXPERTISE

Morgan's global footprint enables the company to supply a customer's needs anywhere in the world, which means local and global expertise that Morgan can leverage, which Hulse is keen to demonstrate.

"We have a wide range of engineering capabilities; we have specialist engineering teams; we have installation support to help to not only design the solution but also to help with the installation and the actual running of it," she said. "We have the ability to support on assessing how the heat-treatment equipment is working, whether it's through using infrared cameras to assess the condition of the equipment or just to help with the profiles at which we run the equipment. We have the technical knowhow, and we also have dedicated research and development to bring on new and improved products to the market continuously."

Finding high-tech and innovative solutions to its customers' problems are, ultimately, what makes Morgan tick, according to Hulse.

"This is an end business for us; this is the core of who we are," she said. "We get very excited and probably a little nerdy about how we approach these challenges."

Through its extensive product portfolio and worldwide facilities, Morgan has adopted a leading position within the fields of international projects such as CPI, iron and steel, and power generation.

"We have the ability to successfully apply single-order sourcing across the barriers of cultural understanding, language differences, international trading, and border control," Hulse said. "We have so much experience that we give our customers a sense of confidence and trust. And that further strengthens our international positioning."

## "TAILORED SOLUTIONS"

A recurring theme that runs throughout Morgan is what Hulse calls "tailored solutions."

"It applies to our engineering services, which provide carefully tailored combinations of our products to meet a specific need, all the way through to R&D, which is familiar with working with major industries and universities to produce new technology required by tomorrow's industry," she said. "I think it's a combination of: what do we do in the short term, and how do we make sure that we take time to leverage our previous experience but listen to specific current needs and future needs of our customers? Then we leverage the necessary R&D and the engineering services and our broad cultural and global footprint to really serve their needs and meet them where they are — making it easy for them to achieve their goals."

## MORGAN ADVANCED MATERIALS

Morgan backs up that promise of guaranteeing a solution with 163 years of experience.

Morgan began in 1856 as Morgan Crucible, and after more than 160 years of continuous trading, Hulse said Morgan continues to operate in the same space it started in, although it's obviously expanded in many directions since then. The company is now officially known as Morgan Advanced Materials, a PLC headquartered in Windsor, U.K., listed on the London Stock Exchange.

"Our purpose is to use advanced materials to help make more efficient use of the world's resources, and to improve the quality of life," she said. "All of it comes down to the engineering of high-performance materials and specialized products that go after reliable solutions to the technical challenges that our customers have. We can help our customers achieve more with less."

Despite Morgan's continuing innovations, Hulse emphasized the company's most fundamental product is still the crucible.

"I'm pretty proud of that," she said. "We haven't walked away from our core; we've built on it. And with thermal ceramics, we have been the one that has continuously revolutionized the high-temperature insulation market. That's been ongoing since the 1990s when we introduced Superwool® low biopersistent fiber technology. And now we have introduced Superwool XTRA® fiber, the latest in this family, a breakthrough technology as this particular material has no crystalline silica formation."

## FINDING SOLUTIONS TO FUTURE PROBLEMS

Morgan is always striving to stay ahead of the curve, to stay ahead of requirements and make sure the company is finding solutions to its customers' future problems, according to Hulse.

"I'm very proud of that, and the team is so committed to continuously look for new ways to meet the needs of the customers and partner with them to enable their success," she said.

As Morgan drives forward in its second century of business, Hulse said Morgan is diligent in its mission to supply thermally efficient lining in order to heighten the demand of energy while lowering carbon dioxide emissions.

"That's going to mean that we have to develop more and more precise solutions to meet the heat-treatment needs," she said. "Government agencies are laying on more requirements for our customers, and we all try to do well by the world in which we live. We believe that we can make a difference there by helping to anticipate those needs and then really helping to save energy and to reduce the emissions output. I think there are companies who have already recognized us for this, and we've been partnering with some of them for a long time."

With that in mind, Morgan will continue to offer its customers the best solutions to meet all their needs, according to Hulse.

"It doesn't sound like a sexy business from the outside, but I think that we're doing some really revolutionary things with a product that's been around for a very long time, and we're continuously striving to make it new and fresh and better performing," she said. "I'm really delighted to see where we've come from. We have more in our bag to unveil over the next couple of years, and we're going to continuously be pushing to have the solutions available as our customers need them."

**MORE INFO** www.morganthemalceramics.com

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# Q&A /// INTERVIEW WITH AN INDUSTRY INSIDER

STEVE MUELLER /// ASSOCIATE DIRECTOR, BUSINESS DEVELOPMENT /// PRAXAIR, INC.

## *"The best way that we could help a customer with a challenge is to understand their needs and use our gas application expertise to evaluate their gas system and suggest options for improvement."*

**What does Praxair do for the heat-treat industry?**

Praxair produces and sells industrial gases, such as nitrogen, argon, hydrogen, and helium. Our main focus for the heat-treat industry is on atmospheres, but our gases are used in several applications including annealing, brazing, carburizing, sintering, and quenching. We also offer services, such as heat- treatment process evaluations, furnace audits, and technical assistance to help improve furnace performance. We have been working in this industry for a long time and have partners that can provide additional resources around gas controls, sensors and meters. Our goal is to provide the ultimate measure of customer service and support to the heat-treat industry.

**What's a typical day like for you at Praxair?**

My job is really kind of fascinating in that I work with a lot of different people and with various teams throughout the company. We have application engineers in the field that help our customers with their heat-treatment issues and look for new opportunities. This team has years of experience and they have become valuable resources for our customers. They provide a good perspective on what is happening in the heat treatment field.

I also work with our research and development group to design new types of heat-treatment products that serve the industry. Together, we evaluate the market to identify new improvements in existing heat treatment applications and look at new applications to bring a better understanding to the heat treat customers, from an industrial gas standpoint. I also visit them to see first-hand what things they are working on. I enjoy that part of my job very much, because it gives me an opportunity to see where our gases are applied and determine where improvements can be made. I also work closely with our marketing and communications group to develop plans and reach our heat-treat audience. Any one of these or all of them can be part of my typical day here at Praxair.

**How do you work with a customer who comes to you with a challenge?**

The first thing we generally do is try to get a good understanding of what their process is and what their challenges are. We have experienced people in the field who can help them and provide a new or maybe different approach to their issues. There may also be a situation where we work with some of our partners to bring a customized full-service package and help them overcome whatever is hindering their progress.

So, my feeling on this is, the best way that we could help a customer with a challenge is to understand their needs and use our gas application expertise to evaluate their gas system and suggest options for improvement.

**What do you think has changed the most about the heat-treat world, and how has Praxair adapted to that?**

I think the largest changes in the heat-treat world come in two different areas. When I first started in this role five years ago, there wasn't as much reliance on automation and there was more reluctance to change. I see the heat-treatment industry now adapting newer technologies, looking at more modern ways of approaching issues, and getting better performances out of their heat-treatment equipment.

Some applications have grown more than others over the last few years. Vacuum carburizing and hot isostatic pressing have seen decent growth numbers. It will be interesting to see how 3-D metal printing affects the heat-treatment market in general.

**What would you consider some of Praxair's proudest achievements?**

We're an industrial gas company that's been around for over 100 years. We have a large footprint here in the United States, and now globally as we merge with Linde. In heat-treatment, we bring resources and knowledge into the industry in an effort to help our customers. I'm most proud when we are approached by our customers with an issue, and we can help them resolve it and improve their process. I'm proud of our team's expertise and their ability to connect with the heat-treatment industry. Our team has maintained many good relationships over the years and those relationships have allowed us to partner with our customers to better understand their processes and business objectives.

**Where do you see the heat-treat industry in the next, say, 10-20 years, and Praxair's place in that future?**

I think the heat-treat industry is going to continue to evolve and become more modern. It will also continue to adapt newer controls and other types of monitoring systems that will provide better performance for heat-treatment applications.

**MORE INFO** www.praxair.com/ heattreating