Technologies and Processes for the Advancement of Materials

Thermal processing

ISSUE FOCUS ///

SINTERING / ADDITIVE MANUFACTURING

A MATERIAL DIFFERENCE: WHY A METAL MANUFACTURER OPTED FOR PLASTIC

CONFERENCE PROFILE ///

WorldPM

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FROM THE EDITOR ///

WorldPM2026 is here!

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.

By the time you may be reading this, many will be arriving at WorldPM2026 — the primary source for metal powder technology transfer — in Montreal, Canada. This marks the first time the conference has been in North America in six years.

WorldPM, presented by the Metal Powder Industries Federation (MPIF), is the largest global powder metallurgy and particulate materials event of the year. The PM industry comes together at WorldPM, but also for two more conferences as well. The other shows making up this hat trick of PM are AMPM2026 and Tungsten2026.

The 2026 show will boast in-person interaction for business deals, information exchange, and panel discussions on the latest innovations in the industry.

But, if you're not lucky enough to be walking the floors of WorldPM this month, this issue also has a few entries that take on the topics of additive manufacturing and sintering.

In addition to our main articles, make sure you check out our columnists. They're always offering up must-know expertise on a variety of important heat-treating subjects.

I also want to guide you to this month's Q&A. Women in the industrial sector has always been an important topic of conversation since I have been editor of *Thermal Processing*, so I want to make sure you don't miss this feature. In it, I talk with Tormach's Amanda Lucas and Kimberly Upton on why it is vital for companies to see the advantages that come with a diversified workforce.

As we take the plunge into summer, I'd like to take this moment to remind you to let *Thermal Processing* be your eyes, ears, and, most importantly, your voice. No matter the challenges you face, we are here, first and foremost, to shine a spotlight on your valuable products, services, and know-how.

Whether it's a powerful ad or an expert article, let us share your insights with the people who are searching for it.

Stay cool, and, as always, thanks for reading!

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Teresa Cooper
PRESIDENT

Five of Tenova's innovative techniques are included on the INCITE platform for clean EU technologies, underscoring Tenova's role as key enabler of a sustainable and circular EU economy. (Courtesy: Tenova)

Tenova's advanced solutions featured on INCITE platform

Tenova, a leading developer and provider of sustainable solutions for the green transition of the metals industry, has five of its innovative techniques mentioned in the European Innovation Centre for Industrial Transformation Emissions (INCITE) web platform. Launched in 2024, INCITE identifies and evaluates emerging cutting-edge technologies and processes committed to decarbonization, depollution, and the increase of resource efficiency and circularity.

Among the technologies featured on the platform are Tenova's solutions for steel production, including electric arc furnace (EAF) with Consteel® and Consteerrer® technologies, the open slag bath furnace (OSBF) for melting DRI, the iRecovery® and heat leap systems for heat recovery from EAF plants, Tenova KT for polymer injection in EAF, and Energiron for direct reduced Iron (DRI) production, jointly developed with Danieli.

The INCITE platform provides a comprehensive overview of the environmental benefits and performance, technology maturity, possible trade-offs, location, and costs benefit elements of these technologies. Of the five Tenova solutions, three are already fully operational:

Consteel®, a well-established EAF technology with more than 80 installations worldwide, is an efficient steelmaking process in which raw materials are continuously heated and charged into an EAF, where they are melted by immersion in the liquid steel present in the furnace, while simultaneously controlling gaseous emissions. Thanks to a joint technological effort and close collaboration, Tenova and ABB have co-developed and successfully implemented Consteerrer®, enabling faster, safer, and more cost-effective liquid steel production.

iRecovery® is one of the leading technologies for recovering and reusing the thermal energy of off-gases directly within the EAF melting process — energy that is typically lost through steam generation. The saturated steam acts as an energy carrier for internal use, electricity generation, and district heating. The integration of the heat leap system, a high- performance heat pump, further enhances energy recovery by using low-temperature heat from the EAF cooling water to supply district heating networks.

Energiron, jointly developed by Tenova and Danieli, is a direct reduction process (DRP) that enables the production of reduced iron (DRI or HBI) using a vertical shaft furnace. This technology is among the leading solutions implemented worldwide for low-environmental- impact DRI production, thanks to the use of natural gas and hydrogen. DRP are typically followed by electric arc furnaces (EAF) to produce liquid steel (DRI/EAF process).

The other two Tenova solutions also included are:

» Open slag bath furnace (OSBF), currently under development and commercialized as iBlue®, is an AC electric furnace designed for melting DRI and producing pig iron. The intent of combining a direct reduction plant with a reducing furnace technology like the OSBF is primarily driven by the need to reduce carbon emissions associated with conventional pig iron production by the blast furnace route.

» Tenova KT Twin SRA and Tenova KT Multi enable the injection of recycled polymers as a substitute for coal through two specific systems that can be installed on the EAF wall. The former combines a supersonic oxygen injector with a polymer injector, while the latter allows the injection of both recycled polymers and lime using the same device.

In the RFCS OnlyPlastic project, funded by the European Commission, both injectors demonstrated good performance in terms of slag foaming, without carryover of solid material into the off-gas extraction system.

"We are very proud that Tenova's innovative technology appear on the INCITE plat-

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.

Optris' EtherCAT, pictured, and IO-Link enhance performance and integration into modern automation environments. (Courtesy: Optris)

form — confirming our role as pioneering developers of advanced and sustainable steelmaking techniques," said Enrico Malfa, R&D director at Tenova.

MORE INFO www.tenova.com

New interfaces expand Optris CTi pyrometer series

Optris GmbH & Co. KG is specifically expanding its CTi pyrometer platform with the digital interfaces EtherCAT and IO-Link. This makes the compact, modular infrared pyrometers of the CTi series even more efficient and integrates them more easily than ever into modern automation environments.

With EtherCAT, users benefit from extremely short response times and high synchronization accuracy. Especially in fast processes — such as metal processing or automated production lines — this enables precise real-time temperature control. At the same time, CPU load in the control system is reduced, increasing overall throughput. Thanks to flexible topologies, CTi pyrometers can be integrated directly into existing machine concepts without additional infrastructure.

Commissioning is also significantly simplified: automatic addressing, high immunity to interference, and fast fault detection ensure minimal installation and maintenance effort. Thanks to its short integration times, EtherCAT enables cost-effective implementation while delivering outstanding performance in terms of high data transfer rates and short cycle times.

With IO-Link, Optris further expands the CTi series with a particularly user-friendly interface for the field level. Standardized three-wire cables significantly reduce wiring effort, while automatic parameterization in the master enables fast sensor replacement without downtime. In addition, users benefit from extended diagnostic functions and continuous condition monitoring. Digital data transmission ensures high measurement accuracy of the CTi pyrometers, while parameters can be adjusted remotely at any time—ideal for hard-to-access or safety-critical areas.

With the integration of EtherCAT and IO-Link, the CTi series evolves into an even more flexible platform for Industry 4.0 applications. The combination of precise, non-contact temperature measurement, fast data processing, and intelligent communication enables optimized process control and higher system availability.

"With EtherCAT and IO-Link, we are taking the CTi platform to the next level," said Andreas Rotärmel, product manager at Optris. "Our customers benefit from faster integration, greater process reliability, and maximum flexibility in their applications."

The CTi pyrometers thus combine their proven strengths — robust design, separate electronics box with display, and flexible interfaces — with state-of-the-art communication standards, opening up new possibilities in networked production environments.

Optris GmbH & Co. KG was founded in 2003 and has established itself as one of the leading manufacturers of non-contact temperature measurement devices. Its product portfolio consists of both wearable and stationary infrared thermometers and online infrared cameras for thermographic real-time analyses. Optris develops and produces in Germany to ensure the highest standard in quality as a key component of its company policy.

MORE INFO www.optris.com

Aichelin Americas partners with Wm. Wright & Associates

Aichelin Americas announced a new strategic partnership with Wm. Wright & Associates, effective May 9, 2026. Through this agreement, Wm. Wright & Associates represents a broad portfolio of thermal processing technologies, equipment, and services across the Aichelin Americas group.

This partnership strengthens Aichelin Americas' commitment to delivering enhanced regional support and improved access to its comprehensive range of solutions.

Under this agreement, Wm. Wright & Associates will support the promotion and delivery of solutions from leading brands within the Aichelin Americas group, including:

- AFC-Holcroft.
- Nitrex.
- G-M Enterprises.
- UPC-Marathon.

The portfolio includes:

- Aluminum furnace systems and heat-treating equipment.
- Atmosphere generation systems and process control technologies.
- Sensors, probes, analyzers, and advanced instrumentation.
- Spare parts, hot zones, and critical components.
- Digital platforms, including QMULUS software and engineered solutions.
- Replacement parts, system upgrades, and modernization solutions.
- Field services, rebuilds, repairs, and service contracts.

By partnering with Wm. Wright & Associates, Aichelin Americas enhances its ability to provide localized expertise backed by global engineering and manufacturing capabilities.

Customers will benefit from:

- Faster response times and improved regional accessibility.
- Dedicated technical support and application expertise.
- Streamlined access to integrated equipment, software, and services.
- Enhanced lifecycle support for both new and existing installations.

This collaboration reflects a continued focus on delivering complete, end-to-end solutions to manufacturers across a wide range of industries. From new equipment installations to upgrades, digitalization, and aftermarket support, the partnership enables a more connected and efficient customer experience.

Aichelin Americas is a leading provider of industrial furnace systems, thermal processing technologies, and digital solutions.

Through its group companies — AFC-Holcroft, Nitrex, G-M Enterprises, and UPC-Marathon — the organization delivers advanced equipment, process control technologies, and lifecycle services to manufacturers worldwide.

MORE INFO www.afc-holcroft.com

The pilot-scale PGA platform by Retech will enable advanced powder development for next-generation materials essential to high-performance manufacturing and emerging technologies. (Courtesy: Seco/Warwick)

U.S. national lab selects Retech PGA platform

Retech, a Seco/Warwick Group company, has been contracted to supply a plasma gas atomization (PGA) system to a leading U.S. national laboratory in support of a strategic critical materials initiative.

The pilot-scale PGA platform will enable advanced powder development for next-generation materials essential to high-performance manufacturing and emerging technologies. Designed with flexibility and scalability at its core, the Retech PGA system allows researchers to transition seamlessly from process validation to broader industrial deployment.

National laboratories play a vital role in bridging the gap between metallurgical discovery and manufacturable solutions. While early-stage research confirms material properties, pilot-scale systems demonstrate process reliability, repeatability, and economic feasibility.

Retech's PGA platform is engineered to address these challenges by offering precise process control, feedstock versatility, and the ability to scale parameters in alignment with future production systems.

The system will support efforts aimed at strengthening domestic supply chains and reinforcing U.S. technical leadership in strategically important materials.

"National labs are focused not only on proving what's possible, but on proving what's practical," said Earl Good, Retech president. "Our PGA platform is built to give them a pathway from controlled pilot-scale experimentation to scalable, production-ready capability.

We design our equipment so that once a process is validated, scaling it up becomes a streamlined next step rather than a redesign."

Beyond individual equipment capabilities, Retech's modular platform approach allows integration with existing lab infrastructure, consolidating operations, maintenance, and training across multiple systems.

This integrated strategy enhances cost efficiency while maintaining the high purity and performance standards required for advanced materials applications.

MORE INFO www.secowarwick.com

Important conferences through 2027

The 7th Asian Conference on Heat Treatment and Surface Engineering of Materials (7ACHTSE2026) will be in Chengdu. (Courtesy: Shutterstock)

7th Asian Conference on Heat Treatment and Surface Engineering
September 10-12, 2026
Chengdu, China

The 7th Asian Conference on Heat Treatment and Surface Engineering of Materials (7ACHTSE2026) will be in Chengdu, Sichuan Province, China, September 10-12, 2026. The conference will focus on the latest research progress, technological frontiers, and future trends in the field of material heat treatment and surface engineering and is committed to promoting deep integration and collaborative innovation in this field in the Asian region.

The Asian Conference on Heat Treatment and Surface Engineering of Materials (ACHTSE) is an important series of international conferences jointly initiated by China, Japan, South Korea, and other countries. It focuses on the latest research and developments in surface engineering and heat treatment.

DEADLINES

- **Extended abstracts/full papers submission:** July 31, 2026.
- **Notification of acceptance:** August 5, 2026.
- **Early bird registration:** August 31, 2026.

31st IFHTSE World Congress
October 13-15, 2026
Cologne, Germany

The 31st IFHTSE World Congress is organized by AWT – Arbeitsgemeinschaft Wärmebehandlung + Werkstofftechnik e. V. and will be in Cologne, Germany, October 13-15, 2026, at the International Conference and Trade Fair.

In addition to the World Congress, the event will also feature HK 2026 and the European Conference on Heat Treatment 2026.

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

The largest European congress on topics of heat treatment and materials technology, manufacturing and process engineering in 2026 is organized in cooperation with the International Federation for Heat Treatment and Surface Engineering (IFHTSE) as well as the European heat treatment associations from France, Austria, Switzerland, the Czech Republic, Slovakia, and the Benelux countries. Due to the expected number of lecture registrations, the congress event is planned as a three-day event. The language of the conference will be English.

The 31st IFHTSE World Congress will be in Cologne, Germany. (Courtesy: Shutterstock)

TOPICS

HeatTreatmentCongress, IFHTSE World Congress, ECHT 2026

- Heat treatment – processes, systems, media, safety.
- Sustainability concepts for heat treatment plants and process chains.
- Artificial intelligence, simulation and digitalization.
- Production and processing of components in the process chain.
- Properties of components in processing.
- New material developments.
- Material analysis and quality control.

Steel Innovation

- Materials Engineering steel.
- Digital steel technology.
- High strength and wear-resistant steels.
- Sustainable steel – recycling, re-use and re-manufacturing.
- Corrosion-resistant steels.
- Hydrogen embrittlement / steel development for the hydrogen economy.
- Materials testing for steel.
- Increasing the damage tolerance of steels.
- New steel concepts for additive manufacturing.

CROSS GLOBAL INDUSTRY HIGHLIGHT

In addition to the extensive scientific and technical program, attendees will have the unique opportunity to experience a major international exhibition and trade fair with approximately 150 exhibitors. Leading companies from around the world will present their latest developments in equipment, services, operating materials, and other relevant technologies essential for the heat treatment and surface engineering industries. The exhibition will provide invaluable networking opportunities and foster collaborations between academia and industry.

DEADLINES

- **Notification of abstract acceptance:** May 15, 2026.
- **Deadline for proceedings manuscript (extended abstract 2-4 pages):** July 15, 2026.

MORE INFO www.hk-awt.de

32nd IFHTSE World Congress | ECHT 2027
Milan, Italy
April 14-16, 2027

Organized by Associazione Italiana di Metallurgia, this event combines the IFHTSE World Congress and ECHT. The event is dedicated to researchers, engineers, metallurgists, and industry leaders seeking to bridge the gap between laboratory innovation and large-scale industrial application.

- **Conference Chair:** Prof. Massimo Pellizzari.
- **Co-Chair:** Lesley Frame (IFHTSE President).

DEADLINES

- **Abstract Submission Deadline:** November 20, 2026.
- **Notification of Acceptance:** January 15, 2027.
- **Early Bird Registration:** February 5, 2027.
- **Full paper or extended abstract:** March 5, 2027.

MORE INFO www.aimnet.it/eng/echt2027-32ifhtse.shtml

INDUSTRIAL HEATING EQUIPMENT ASSOCIATION

IHEA in motion: Successes, insights, and the road ahead

The Industrial Heating Equipment Association (IHEA) continues to strengthen the industry through focused training, meaningful connections, and initiatives designed to help members grow, collaborate, and move forward. IHEA members contribute their time and expertise to provide technical information and the necessary tools to assist those in the industrial heating industry. Whether you're looking to connect with industry professionals, explore technologies through flexible virtual learning, access in-depth training resources, or pick up practical tips from webinars, IHEA offers a variety of opportunities to support your growth. Bookmark www.ihea.org to explore IHEA's programs and events.

HANDS-ON LEARNING SPARKS INTEREST IN INFRARED CURING

For several years, the Infrared Equipment Division (IRED) of IHEA has partnered with the Chemical Coaters Association International (CCAI) to provide the Powder Coating and Curing Processes seminar. In May, this outstanding training course was at the Alabama Power Technology Applications Center in Calera, Alabama, which provided the perfect training facility for attendees.

The combination of expert classroom instruction coupled with hands-on learning in its training lab proved to be beneficial for everyone involved. The IRED portion of the seminar generated a lot of interest on infrared curing processes and real-world applications. Scott Bishop of EPRI delivered a fascinating demonstration using various heating devices during the presentation to drive home the concept of infrared curing.

Additional speakers contributing to the seminar's success from the IRED were John Podach with Fostoria Infrared and Michael Stowe with Stowe & Sons PLLC.

TECHNICAL TRAINING MEETS FLEXIBLE LEARNING

IHEA's online courses have been a successful source of high-level education for those who prefer a virtual learning experience. The Fundamentals of Industrial Process Heating will run from October 26 through December 13, 2026. This extensive six-week course provides a basic understanding of process heating, and an engineering background is recommended to take this course. The curriculum includes the basics of heat transfer, fuels and combustion, energy use, furnace design, refractories, automatic control, and atmospheres as applied to industrial process heating. Weekly coursework, quizzes, and a final exam project are administered to guide students on their progress and evaluate their knowledge of the material.

Moderator interaction is available during the weekly forum discussions and via email for questions and to review the coursework. Registration fee includes the online course materials sent electronically. A printed version can also be purchased. Students successfully completing the course will receive a certificate of completion noting 18 PDHs. The course fee is $775 for IHEA member, $950 for nonmembers. For a complete listing of the topics covered and registration information, go to www.ihea.org/event/FundamentalsFall26.

EXPLORE IHEA'S LIBRARY OF ENERGY-FOCUSED WEBINARS

IHEA has built a library of topics focusing on carbon-producing heating processes. The webinars provide methods to optimize efficiency and thereby reduce carbon emission intensity. Additionally, these webinars cover the various scopes of carbon emissions and methods to determine your site's or your specific equipment's carbon footprint. The available DOE tools and other resources for determining and reducing your carbon footprint are also discussed. Overall, this webinar series gives viewers an excellent overview of carbon emissions, how to determine them, and how to reduce them. To access the free sustainability and energy management webinar library, go to www.ihea.org and click "Sustainability Past Webinars" under the Sustainability tab.

LEARN AND CONNECT AT IHEA'S FALL SEMINARS

IHEA's annual Combustion Seminar and Safety Standards and Codes Seminar will take place concurrently in Charlotte, North Carolina, November 17-18. Led by seasoned industry professionals, these popular training classes offer two days of in-depth instruction enriched with real-world examples. Attendees will have the opportunity to engage directly with expert speakers and get answers to their questions. Enhancing the experience, the fall seminars also feature a tabletop exhibition showcasing leading suppliers and innovations from the thermal-processing industry.

The Combustion Seminar includes 16 sessions designed to give vast exposure to combustion technology, led by industry professionals in a non-commercial environment. The seminar also includes a session on hydrogen and decarbonization. The Safety Standards & Codes Seminar provides a comprehensive review of the NFPA 86 standard as well. Attendees receive a copy of the standard with registration.

Admission to the tabletop exhibition is included with the seminar registration fee. Registration will be open soon at www.ihea.org/events under the events & training tab.

IHEA'S ENERGY MANAGEMENT SUMMIT IS GOING VIRTUAL IN 2026

Mark your calendar for December 2 and 3 when IHEA's popular annual SUMMIT takes a deep dive into energy management and sustainability. IHEA believes this is an ever-evolving issue in our industry, and it's important that IHEA continues to provide quality education and information to the industry as we make this journey together. Scheduled for the afternoon of December 2 and the morning of December 3, this format will allow you to participate without the cost of travel.

Presentations topics will include:

- Highlight economic and energy savings, and profit improvements.
- Introduce new technologies for energy management.
- Explore where will we be 10 years from now.
- Deliver case histories from around the globe.

Sponsorships available: Promote your company and support the SUMMIT by becoming a sponsor. IHEA members receive a 10 percent discount off sponsorship fee.

Sponsorship includes:

- Two complimentary registrations.
- Logo on event website.
- Logo in all promotional eblasts.
- Logo in event promotion brochure.
- Logo on welcome slides during SUMMIT.
- Recognition on IHEA social media channels once per month starting in June.

Mark your calendar and watch for more details at www.ihea.org/event/SUMMIT26.

JASON MEYER
MECHANICAL ENGINEER /// DANTE SOLUTIONS

Excessive distortion can be a problem during heat treatment of parts. Modeling can help understand the factors that contribute to part distortion.

Bending under pressure: Controlling distortion

Distortion from heat treatment is a main concern because heat treatment is often one of the last steps in the manufacturing process. Excessive distortion can ruin hours of work on parts that are machined and hardened. Reworking the parts may be challenging, and scrapping the parts leads to lost revenue. In 1995, the German Research Association of Drive Engineering estimated annual losses of ~850M Euros to remove distortion from manufacturing [1]. Around the same time DANTE, a heat-treatment process modeling tool, was born from a project with the American automotive industry, academia, and the national labs, to combat distortion in excess of hundreds of millions of dollars annually.

All distortion from heat treatment can be broken down into two categories: shape change and size change. Size-change distortion is caused by the reorientation of the crystal structure as the steel changes phase and is unavoidable. Shape change is the difference in part dimensions before and after hardening, assuming no volume change. Shape and size change is caused by material, geometry, and process effects. Material effects refer to the initial state of the steel, including the microstructure phases, chemical composition, carbide phases and sizes, alloy segregation, grain size, and the effects from the material fabrication process. Part geometry affects distortion due to differences in heating and cooling between thick and thin sections, causing material strain. Process uniformity and consistency directly affect part distortion during heating and cooling due to the accompanying phase transformations. Chemical gradients of carbon and nitrogen play a role in nonuniform phase transformations due to their effect on martensite start temperature. The volume change from tempering martensite can have a similar effect if the thermal gradient is high. Process consistency and residual stresses from previous processes also impact process distortion.

To accurately model the distortion from heat treatment, the model must include thermomechanical and phase transformation behavior. A multi-phase plasticity model captures the stress and deformation during the phase transformations and must include the mechanical properties over a wide range of parameters such as carbon level and temperature. Understanding the equipment behavior and the equipment/part interaction in the form of heat transfer coefficients is needed to accurately describe the heat transfer, and temperature gradients, within the part. Heat-treat process modeling can show the root causes of part distortion and potential measures that can be taken to reduce it.

CASE STUDY

A Ferrium C64 bevel gear was selected for a modeling case as it is known to have difficulty in controlling the taper distortion in the teeth during heat treatment. All exposed surfaces are carburized using a low-pressure carburization process, typical of aerospace heat-treatment methods for these types of gears. Since taper distortion is the main modeling objective, the gear geometry can be simplified by modeling only a single tooth to reduce computational costs. A finite-element mesh consisting of nodes and elements is created to simulate the car-

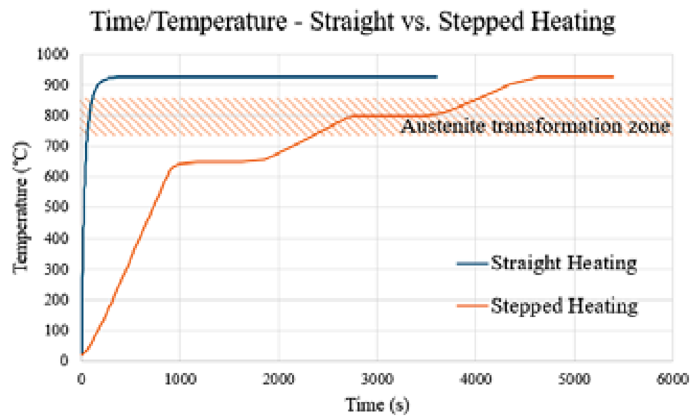

Figure 1: Time/Temperature plots for straight heating and stepped heating models.

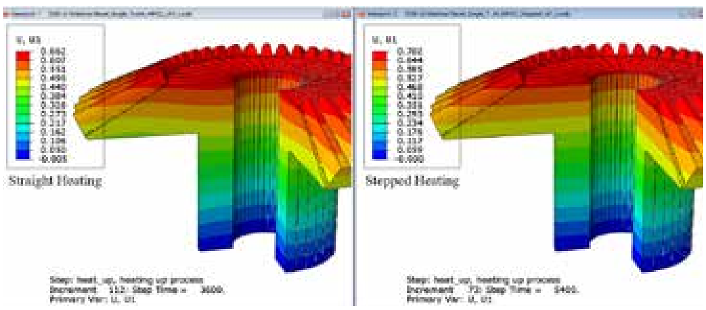

Figure 2: Axial distortion contours for the straight heating and stepped heating models.

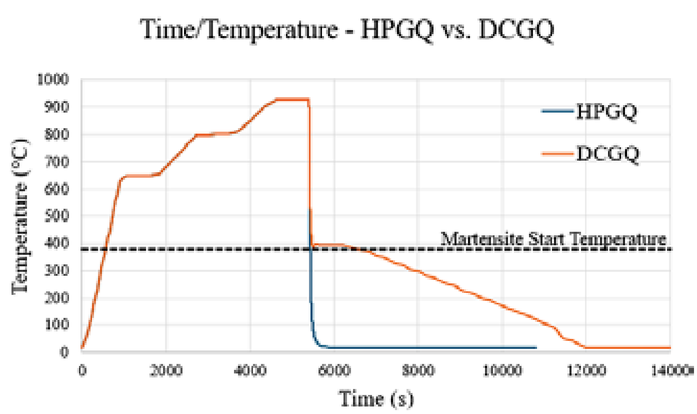

Figure 3: Time/Temperature plots for the HPGQ and DCGQ models.

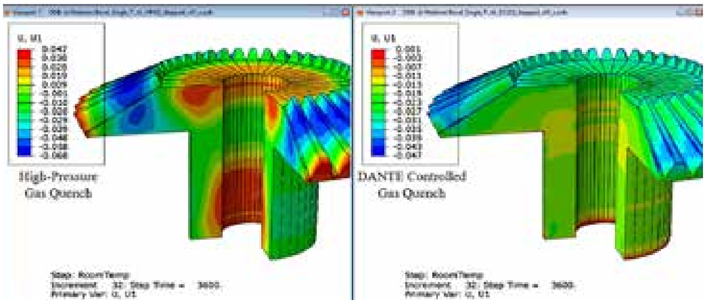

Figure 4: Axial distortion contours for the HPGQ and DCGQ models.

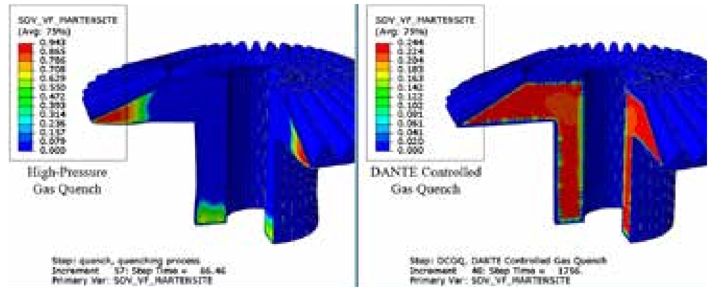

Figure 5: In-process martensite contours for HPGQ and DCGQ processes.

bon, thermal, phase transformation, and stress gradients developed within the part. Additional model assumptions include martensite as the initial phase and a uniform heat-transfer coefficient applied to the outer surfaces for simulating the heating and quenching processes. The study starts with a furnace heating model to predict distortion during heating. Two models were developed, with a straight-furnace heating and a stepped heating to compare the distortion from heating alone. The time/temperature history of a surface point, or node, from each of the models is shown in Figure 1. The straight heating model assumes the part is placed into a furnace preheated to 912°C. The stepped heating model assumes the part is heated to 650°C and is allowed to reach thermal equilibrium. The furnace is then heated to 800°C and held for another 15 minutes until finally heating to the 912°C holding temperature. The temperature holds help control the thermal gradient in the part before and during the transformation to austenite ensuring the phase transformation happens more uniformly throughout the part.

This case study reinforces the need to understand the factors that contribute to part distortion, such as part geometry, thermal uniformity, material condition, surface chemistry, and phase transformations.

The results of the two heating models are shown in Figure 2. The contours show axial distortion, to capture the tooth-taper mode, and both models are at the end of heating while the part is uniformly at 912°C. At first glance, the stepped heating model, right, shows a slightly higher magnitude of axial distortion. However, each of the color divisions in the contour are almost perfectly horizontal, showing a uniform expansion from heating in the axial direction. In contrast, the straight heating contour, left, has a "wavier" appearance to the color divisions in the contour, showing non-uniform distortion from heating compared to the stepped heating model.

Following heating, two quench methods are modeled, one with a standard high-pressure gas quench (HPGQ) process and another with a DANTE Controlled Gas Quench (DCGQ) process. The DCGQ process is determined by modeling the quench with a hold just before the martensite transformation to achieve thermal equilibrium, and a design requirement of no greater than 10°C temperature gradient in the part during the martensite transformation. For the DCGQ process, the ambient temperature is controlled to maintain the thermal equilibrium in the part with a series of temperature holding steps. The time temperature plots for the surface node during the two quench models in Figure 3 illustrate the difference in quenching methods. Due to the complexity of the part geometry and the tight temperature gradient requirement, the quench holding steps appear to ramp the temperature down.

Figure 4 shows the stark contrast in axial distortion between the HPGQ and DCGQ models. The HPGQ model shows that the tip of the tooth curls up while the middle of the tooth dips down, contributing to an overall curl of about 115 µm. The bore of the gear also shows some nonuniform axial distortion. The DCGQ model shows an overall shrinkage in the part with the tooth tapering down about 47 µm near the tip. Because of the controlled heating and quenching, the distortion from the DCGQ process is more uniform than from the HPGQ process. If corrective machining were needed to bring the parts within spec, the HPGQ processed gear may need to remove material from the case nonuniformly, reducing the effectiveness of the case-hardening process.

The mechanism behind the increased distortion shown in the HPGQ model can be seen in the in-process martensite contours, Figure 5. When martensite begins to form in the HPGQ model, a large thermal gradient is present in the part. This gradient causes the martensite to form first in the thinner cross sections of the part, such as the tips of the gear teeth, where the cooling is fastest. The temperature is low enough to have a nearly complete martensite transformation, and the associated volume expansion bends the tip of the tooth upwards, causing the taper shown in the final distortion contour. The DCGQ model specifically aims to keep the thermal gradient to a minimum during the martensite transformation, so the transformation occurs more uniformly through the core of the gear, as shown in the right contour in Figure 5.

This case study reinforces the need to understand the factors that contribute to part distortion, such as part geometry, thermal uniformity, material condition, surface chemistry, and phase transformations. Minimizing the thermal gradient within a part during phase change can reduce the nonuniform size and shape change leading to more uniform, or even reduced, distortion. The DCGQ method presented here is particularly suited for high-hardenability steels in which the holding steps during quench can reduce the part thermal gradient while still forming the desirable martensite phase. In applications where tolerances are tight, such as aerospace components, the distortion from heating should also be considered. Heat-treat process modeling can help to gain a better understanding of what is going on behind the black box of heat treatment to get to the root causes of distortion.

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ABOUT THE AUTHOR

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HOT SEAT ///

D. SCOTT MACKENZIE, PH.D., FASM
SENIOR RESEARCH SCIENTIST–METALLURGY, RETIRED

The most common uses of Be-Cu are in electrical applications, such as connectors, terminals, and socket. But these alloys are also used in non-sparking tools and safety-related hardware.

Beryllium-copper alloys

This month, I will be discussing the physical metallurgy of the precipitation hardening beryllium-copper alloys, used in a variety of unique applications such as non-sparking tools and electrical connectors.

INTRODUCTION

Beryllium-copper alloys are unique in that they can be used for applications requiring high electrical conductivity and high strength. The most common uses of Be-Cu are in electrical applications, such as connectors, terminals, sockets, spring contacts, and switch blades. These applications require the high strength, excellent electrical conductivity, and fatigue properties to prevent failure during repeated use. By properly balancing the heat treatment, the optimum electrical conductivity and mechanical properties can be achieved.

Be-Cu is also used in non-sparking tools and safety-related hardware for hazardous environments. Because the alloy does not produce sparks easily on impact, it is selected for oil-and-gas facilities, chemical plants, mining operations, and explosive atmospheres. In those settings, the non-sparking characteristic can be more important than maximum strength.

Spring performance is one of the applications using Be-Cu. This is especially true if the springs require good electrical conductivity, such as flat springs, diaphragms, beam springs, bellows components, and small load-bearing elastic elements. The fine precipitate structure developed on aging gives a high elastic limit, so springs can be cycled many times without taking a permanent set.

The alloy is particularly effective where the spring must also serve as an electrical conductor or where dimensional precision is critical. In such cases, the aged structure provides both mechanical resilience and sufficient conductivity for functional integration. That combination is difficult to match with many other spring materials.

The most common wrought strengthening grades, such as C17200, contain roughly 1.8 to 2.0 wt% Be, while other wrought and cast grades vary in Be content and may also include Ni, Co, or Pb depending on conductivity, machinability, or casting requirements. These additions matter because they can shift precipitation kinetics, modify the sequence, and change the balance between strength and conductivity. In the base Be-Cu alloy, however, the same basic precipitation sequence governs hardening.

BERYLLIUM-COPPER PRECIPITATION SEQUENCE

In many ways, the Be-Cu system can be compared to the Al-Cu system for precipitation heat treatment. As in the Al-Cu alloy system, there is decreasing solubility of beryllium in the copper alpha (α) phase with decreasing temperature. Since there is decreasing solubility as temperature decreases, this satisfies the basic criteria for precipitation hardening. This is seen in the copper rich end of the Be-Cu phase diagram (Figure 1).

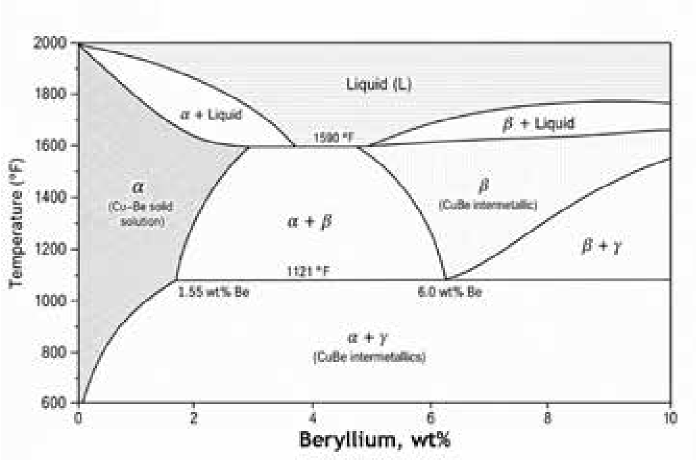

Figure 1: Copper-rich end of the Beryllium-copper phase diagram. At 1,590°F, beryllium has a solubility of about 2.7% in alpha. At room temperature, the maximum solubility is less than 0.2% [1].

At Be concentrations encountered in typical Be-Cu alloys (1.8-2.0%) the precipitation sequence is made more difficult by the beta phase, in the alpha + beta phase field, converting to gamma. However, the essential aging sequence is unchanged.

Beryllium-copper alloys are solution heat treated at approximately 1,500°C (815°C) to bring all the alloying elements into solution. Upon rapid quenching (typically water or polymer), a supersaturated solid solution of Be-α copper results. There is a large thermodynamic driving force for decomposition during aging because of the large solubility gap. It is this large solubility gap that is one reason why Be-Cu alloys can achieve high strengths relative to other copper alloys.

Initially, during aging, there is clustering of the Be atoms in the copper matrix. These very fine clusters form Guinier-Preston zones on {100} matrix planes[2] [3]. The GP zones act as precursors to later coherent precipitates that provide strengthening, and eventually the incoherent equilibrium precipitate.

The basic precipitation mechanism is supersaturated alpha-Cu after quench, GP clustering on {100}, metastable gamma double-prime, metastable gamma prime, then stable gamma equilibrium precipitate (Equation 1):

$$\alpha_{SS} \rightarrow GPZ_{\{100\}} \rightarrow \gamma'' \rightarrow \gamma' \rightarrow \gamma$$

Equation 1

As in aluminum alloys, strengthening occurs before the formation of the equilibrium precipitate, and the onset of coarsening.

The gamma double-prime stage provides the largest amount of strengthening because it is extremely fine and coherent or nearly coherent with the face-centered cubic (FCC) α-Cu matrix. These γ"

Precipitate	γ"	γ'	γ
Stability	Metastable	Metastable	Equilibrium
Crystallography	Tetragonal (BCT)	Tetragonal (BCT)	Body-Centered Cubic
Coherency	Fully Coherent	Semi-Coherent	Incoherent
Typical Location	Uniformly in grains	Uniformly in grains	Coarse at Grain boundaries
Strength State	Peak Strength	Over-aging Beginning	Fully Overaged (soft)

Table1: Summary description of precipitates occurring in Be-Cu alloys [4].

precipitates are extremely small and are observable only through the TEM. They are typically body-centered tetragonal in structure and usually appear as plates or disc-shaped precipitates.

The precipitates grow along the $\{100\}_\alpha$ planes of the copper matrix. Coherency strains make dislocation motion difficult, so even a low volume fraction can produce a large increase in hardness and yield strength.

The gamma prime phase is a metastable semi-coherent phase that appears after gamma double-prime during aging. It occurs before the precipitation of the equilibrium gamma phase. The γ' phase has an ordered body-centered tetragonal (BCT) structure, which is a step closer to the equilibrium body-centered cubic (BCC) structure of the equilibrium precipitate.

The morphology of γ' is either later plate like precipitates, or acicular or needle shaped, compared to the disc-shaped γ". Gamma prime is coherent on the $\{112\}_\alpha$ or $\{112\}_\alpha$ of the copper matrix [4]. While γ' still contributes to the alloy's strength, it typically corresponds to the onset of over-aging, as the γ' grows and consumes the γ" phase, the hardness begins to decrease.

The final equilibrium precipitate, CuBe is an ordered body-centered cubic (BCC) structure, and is an intermetallic, with a 1:1 ratio of copper to beryllium atoms. It is incoherent with the copper matrix.

A summary of the precipitates is provided in Table 1.

Cold work before aging generally increases the rate and sometimes the magnitude of hardening. Plastic deformation raises the dislocation density, which provides heterogeneous nucleation sites and short-circuits diffusion paths. The result is often a faster approach to peak hardness and, in some cases, a higher peak because more precipitates can nucleate on the stored strain field [1] [2] [3].

CONCLUSION

In this article, the basic precipitation sequence of beryllium-copper alloys has been discussed. In a later column, the aspects of heat treatment of beryllium-copper alloys will be provided.

Should you have any questions or comments regarding this article, or suggestions for additional articles, please contact the editor or author.

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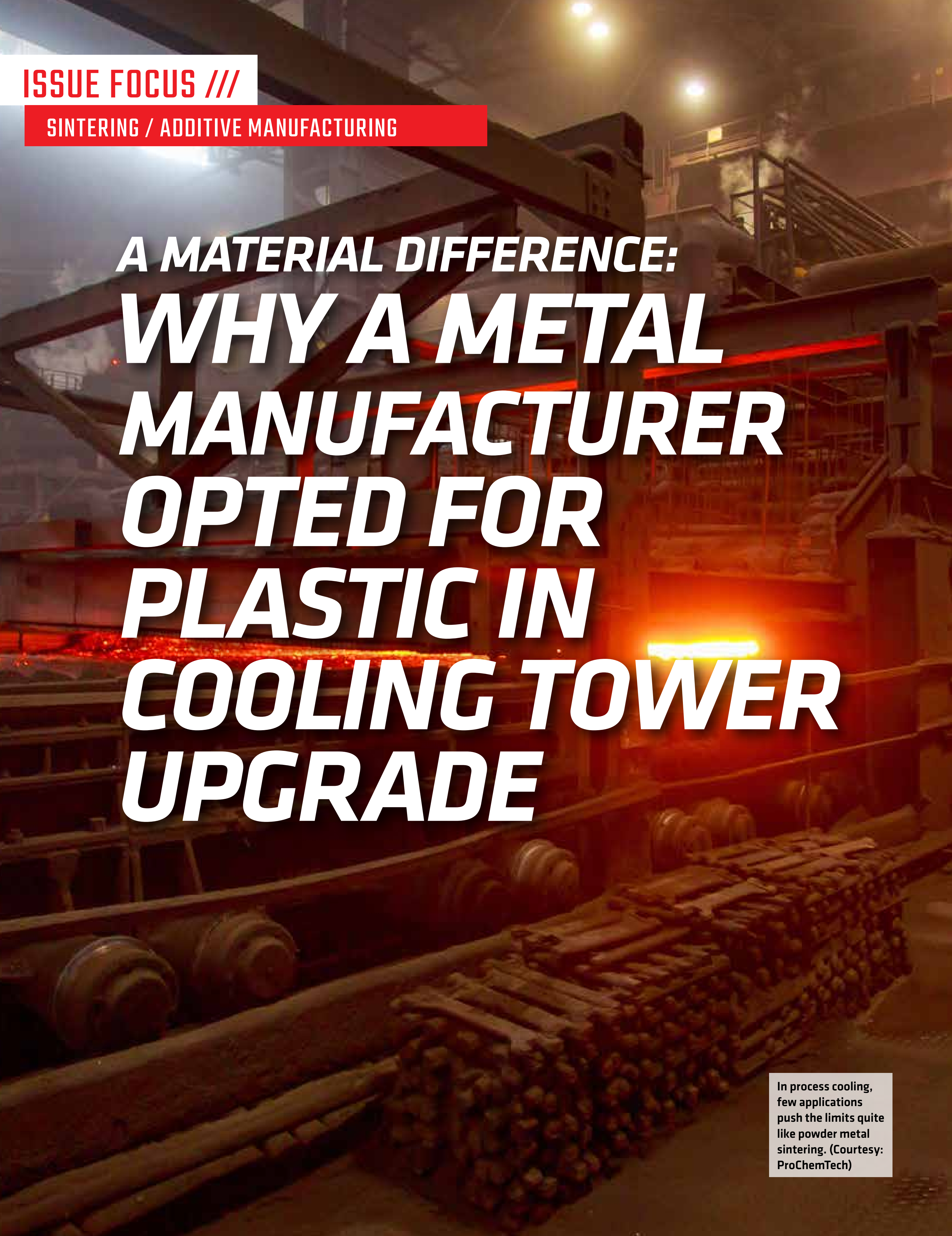
ISSUE FOCUS ///

SINTERING / ADDITIVE MANUFACTURING

A MATERIAL DIFFERENCE: WHY A METAL MANUFACTURER OPTED FOR PLASTIC IN COOLING TOWER UPGRADE



In process cooling, few applications push the limits quite like powder metal sintering. (Courtesy: ProChemTech)

Case study: Sintered metals plant finds long-term reliability and cost savings by replacing corrosion-prone metal towers with corrosion-proof engineered plastic.

By **GREG RANKIN**

In powder metallurgy, material selection is everything. Choosing the right alloy determines whether a component will deliver reliable and long-term performance under intense environmental conditions such as high heat, extreme pressure, or excessive wear. A miscalculation can result in increased maintenance needs, premature failures, and costly downtime for end users.

The same principle applies to cooling towers. These systems are essential to industrial operations, constantly regulating heat loads to keep processes running smoothly. The material used in their construction plays a critical role in determining reliability and longevity. Many towers are built from galvanized metal, which is highly susceptible to corrosion and rust. Over time, this can result in greater maintenance demands, unplanned downtime, and expensive repairs.

For one sintered metals facility in western Pennsylvania, the decision to break away from traditional metal cooling towers was driven by both necessity and experience. Faced with unique high-temperature cooling needs and the financial burden of repeated replacements, the plant opted for high-density polyethylene (HDPE) engineered plastic for its most recent upgrade.

THE HEAT IS ON

In process cooling, few applications push the limits quite like powder metal sintering. Inside a sintering furnace, temperatures in the high-heat zone can reach several thousand degrees Fahrenheit. The process bonds and shapes metal particles using heat and pressure without fully melting the material. This controlled fusion creates strong, precise parts while maintaining the desired material properties.

At the Pennsylvania facility, the water leaving some furnace zones is nearly boiling, requiring a specialized cooling system.

"They have a unique setup with hot and cold wells to manage those temperatures," said Timothy Keister, chief chemist and head of the performance chemical division at ProChemTech.

Here's how it works: Hot water from the furnaces flows into a hot well and is then pumped to the top of the cooling tower. After it is cooled, the water is stored in a cold well before being recirculated back to the furnaces. At the same time, the cold well water is continuously overflowing at a set rate into the hot well to decrease the temperature of the water going to the cooling tower.

"We call this a quench circuit, and it keeps temperatures below the melting point of the tower's internal fill," Keister said.

Due to these extreme operating conditions, the system operates with an unusually high temperature differential. Water enters the cooling tower at roughly 105°F and exits at 85°F — a much larger T than the typical 10°F seen in many industrial cooling applications.

With this kind of heat load, reliability is critical. While some facilities have emergency city water backups to prevent catastrophic furnace damage, if the cooling system fails, production stops.

"There's a lot riding on these towers," Keister said. "Downtime is not an option."

STRONGER BOND FORMED WITH HDPE

For decades, galvanized metal has been the default material for cooling towers. While it can perform well in certain environments, metal is vulnerable to a range of chemical and mechanical stresses that limit its lifespan.

"With galvanized steel, you have to be very careful with your water chemistry," Keister said. "If the pH goes above about 8.2, you get what's called white rust. That eats the galvanized coating right off, leaving bare metal exposed, and corrosion sets in very quickly."

Keister has personally witnessed metal towers disintegrate in as little as five years, and most fall in the 10- to 15-year range.

Even stainless steel, often viewed as the premium option, is not invincible. In areas with high chloride levels, operators risk chloride-stress corrosion cracking, especially at points where the metal has been bent or formed. In some cases, chlorides and certain chemical additives can react to form chlorine, which aggressively attacks stainless surfaces.

"I've seen stainless towers develop pinholes through the bottom within just a couple of years if the water chemistry is not just right," Keister said.

HDPE cooling towers have steadily gained ground in industrial applications because of their ability to solve many of the challenges that plague metal tower designs. (Courtesy: ProChemTech)

The financial implications go far beyond maintenance costs. While a new tower itself might cost anywhere from $80,000 to $150,000, installation can be double or even triple that. Cranes are required to lift the old unit out and place the new one, sometimes requiring nearby rail lines or roads to be closed.

Keister recalls one project where an aging metal tower was so badly corroded that it broke in half mid-lift, nearly causing catastrophic damage to the building below.

"When you add up the cost of replacing the tower and the installation every 10 or 15 years, it becomes incredibly expensive," he said. "If you can avoid those repeat installations, you're way ahead of the game."

HDPE tower lifespans range from 30 to 50 years, dramatically reducing the need for costly replacements and installations.

A COOL DECISION TO SPEC ENGINEERED PLASTIC

When it came time for their latest upgrade, the Pennsylvania sintering plant carefully evaluated its options. The facility needed a 435-gallon-per-minute unit that could meet current production demands while supporting expected growth over the next decade. After reviewing stainless steel and engineered plastic designs, the decision was clear: engineered plastic offered a level of durability, reliability, and long-term performance that metal simply couldn't match.

HDPE cooling towers have steadily gained ground in industrial applications because of their ability to solve many of the challenges that plague metal tower designs. For this plant, several key benefits drove the decision:

» **Corrosion-proof and chemically resistant:** Unlike metal towers, HDPE is completely impervious to rust and corrosion. This resistance makes it ideal for facilities with fluctuating or challenging water chemistry, reducing both chemical costs and maintenance requirements.

» **Seamless, one-piece construction:** Most metal towers are assembled on-site using many pieces, which creates seams that eventually become leakage points. HDPE towers are molded as a single, seamless piece, eliminating this risk entirely.

» **Simpler, lower-cost installation:** Engineered plastic cooling towers are significantly lighter than metal, which means smaller cranes and less complex rigging. This makes them faster and more affordable to install.

While it can perform well in certain environments, cooling towers made of metal are vulnerable to a range of chemical and mechanical stresses that limit their lifespan. (Courtesy: ProChemTech)

For a sintered metals facility in western Pennsylvania, the decision to break away from traditional metal cooling towers was driven by both necessity and experience. (Courtesy: ProChemTech)

MATERIAL GAINS

Working with ProChemTech, the plant selected a Paragon model manufactured by Delta Cooling Towers, which has a maximum cooling capacity of up to 250 tons and comes with a 20-year warranty. ProChemTech supplied the complete package, including the tower, pumps, and central control panel that manages the entire system.

As industrial facilities face increasing pressure to reduce costs, improve reliability, and minimize downtime, many are rethinking their approach to cooling tower materials.

"Just as precise material selection inside the plant's furnaces ensures strong, consistent parts, selecting the right material for the cooling tower will keep those furnaces, and the entire operation, running smoothly for decades to come," Keister said.

ABOUT THE AUTHOR

Greg Rankin is a Houston-based freelance writer with more than 20 years of experience writing for the HVACR, processing, and mechanical engineering industries.

ENHANCING THE PERFORMANCE OF METAL AM PARTS

A review of the adoption of different types of post-treatment processes for extrusion and sinter-based technology.

by ALESSANDRO PELLEGRINI, MARIA GRAZIA GUERRA, ROBERTO SPINA, and FULVIO LAVECCHIA

Material extrusion for metals (MEX/M) has emerged as a cost-effective and versatile additive manufacturing technology (AM) for producing complex metal components. Despite its potential, parts realized via MEX/M suffer from significant limitations, primarily poor surface quality due to the intrinsic layer-wise effect from the printing deposition and selected printing conditions. Furthermore, the multi-step nature of the MEX/M process, particularly the sintering stage, can exacerbate roughness along with the printing orientation, thereby affecting part performance and limiting potential applications. In addition to surface defects, MEX parts are characterized by a high content of porosity when compared to other metal AM technologies such as powder bed fusion laser-based (PBF-LB) and directed energy deposition laser-based (DED-LB). These defects, both on the surface and within the parts, can compromise the mechanical properties and overall quality of the final parts. In this context, the scientific community has increasingly recognized post-treatment processes as essential for simultaneously improving surface quality and enhancing bulk material properties. This review, according to the PRISMA 2020 guidelines, provides a comprehensive analysis of the most critical post-treatment processes applied to MEX/M parts. By critically reviewing the state-of-the-art, this article discusses how these treatments can effectively mitigate outer and inner defects, reduce porosity, and significantly improve mechanical performance, ultimately enabling the broader industrial adoption of MEX/M technology.

1 INTRODUCTION

Material extrusion for metals (MEX/M) is a multi-step additive manufacturing (AM) technology composed of three main stages: printing, debinding, and sintering. The first stage of printing is essential to generating the green part, so the designed part is composed of a mixture of polymers and metal particles. The printing deposition induces in the part the layer-wise effect that characterizes AM technologies. In detail, during the printing, the feedstock can be deposited through the nozzle using a filament-based approach (such as the atomic diffusion additive manufacturing (ADAM) technique proprietary of Markforged Inc.), a plunger-based approach (such as the bound metal deposition (BMD) technique proprietary of Desktop Metal Inc.) or a screw-based one. For each extrusion mechanism, there are corresponding proprietary or commercial feedstock shapes, such as filaments, bars, and granules of pellet [1,2]. Regardless of the different extrusion mechanisms, potential defects can arise, such as inner and outer pores and lack of adhesion between the deposited strands or between the layers [3]. These defects can deteriorate the strength of the parts in further stages. After printing, the debinding is carried out. As for other multi-step sinter-based technologies, such as binder jetting for metals (BJT/M) and metal injection molding (MIM), the debinding is a crucial phase. Indeed, depending on the adopted binder and the volume percentage of metal powder, the selection of how the polymers are to be removed is very important [4]. Solvent-based, thermal-based and catalysis-based approaches are the main types of debinding that can be adopted, or often a combination of two of them is used [4]. During debinding, choosing a balanced combination of time and temperature can prevent the incomplete removal of the polymers. Indeed, when this happens, undesired defects such as blistering, swelling, or cracks may occur on the debound part (or brown part) and, consequently, on the sintered one [5,6]. Finally, the sintering stage is the fundamental phase for providing the desired material characteristics to the designed part. This stage considers different process parameters to drive the part to the desired conditions. In this context, sintering time and holding time are the main drivers. Indeed, a good compromise of time and temperature is fundamental to completing the densification of the powder, obtaining a homogenous microstructure and controlling the shrinkage [7,8]. Moreover, considering sintering theory, heating rate, cooling rate, and atmosphere, each play a fundamental role [7,9]. Along with the printing stage, the sintering stage can also induce various defects on the part, such as residual pores due to an incomplete sintering of the powder, a worse surface quality compared to the green condition, unpredictable shrinkage, and potential oxidation of the surface or carbon and oxygen contamination inside the part [6,10,11].

MEX/M: Parts Criticalities

According to the literature, MEX/M covers a large range of metal alloys from the most common stainless steels (e.g., AISI 316 L and 17-4 PH) [12,13] to tool steels [14], copper (Cu) and its alloys [15], aluminum alloys [16], titanium alloys [17], and superalloys [18]. This wide variety of materials available for MEX/M allows a range of different properties according to the specific application field. However, the multi-step nature of the technology can generate defects on the sintered parts, making them not directly suitable for the desired scope. In detail, the literature confirms how residual porosity and surface defects remain the main challenging aspects for the industrial applicability of MEX/M. These defects appear sometimes hard to avoid because of the extrusion- and sinter-based processes [3]. Achieving the highest densification of the sintered parts is the key target for reaching the intrinsic material properties. Indeed, it appears more frequently that the adoption of customized printing strategies during the deposition can fill the inner voids in the green parts. This is performed by modifying the main influencing parameters (e.g., flow rate) [19] or generating specific algorithms for the deposition path [3,20]. Furthermore, tailored sintering profiles can also provide benefits to the density of the parts and, consequently, to their mechanical properties, microstructure, and shrinkage [21]. Based on the existing literature, the achieved range of sintered density values is between 95 percent and 98 percent of the relative value. This value appears lower than ones typically achieved with other metal AM technologies. Indeed, the residual porosity reduces the load section of the MEX/M parts, which are therefore often mechanically weaker than parts produced by other AM methods. Consequently, the growing interest in MEX/M in recent years prompted the scientific community to consider potential solutions to overcome the current technological limits. Therefore, MEX/M technology is nowadays an affordable and fast solution for the prototyping of metal components, and it is starting to be a good alternative in the manufacturing of fixtures, molds, tools, and spare parts. Nevertheless, the aforementioned criticalities still limit the application scenarios. In this context, the adoption of post-treatment processes appears fundamental to enhancing MEX/M part performance and tailoring the material properties.

The aim of the present review is to provide an overview of the most common post-treatment processes applied to parts produced by MEX/M, specifying their purposes, the properties that can benefit from their implementation, and the potential future perspectives for industrial applications.

2 POST-TREATMENT PROCESSES

Post-treatment processes are usually applied to improve various properties of parts realized through laser-based metal AM technologies. Indeed, the as-built parts derived from laser-based and powder-based technologies are frequently subjected to dedicated post-treatments to reduce thermal residual stress, microstructural instabilities, agglomerates of partially fused powder, and balling effects [22]. According to the literature, several kinds of post-treatment processes can be applied to the metal parts using different technological methods: thermal, mechanical, and chemical [22,23]. Each of these techniques has an effect on the mechanical, surface quality, and microstructural characteristics.

Concerning MEX/M, there is also a large variety of post-treatment processes that can be adopted according to the specific application. In this review, they will be grouped into three categories: heat treatments (HT), surface treatments (ST), and machining technologies (MT).

Following the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) guidelines, this review article employed a systematic search strategy as reported in [24]. Relevant studies on the MEX/M post-treatment processes on as-sintered parts from the last five years were considered. Indeed, from this analysis, articles based on the adoption of post-treatment processes on polymer parts produced through MEX and on green parts produced through MEX/M are considered unsuitable. As reported in the PRISMA flow chart (Figure 1), Scopus, Google Scholar, ScienceDirect, and Springer databases are used for the analysis.

Once enough papers were chosen, the selected papers were first analyzed and classified according to the main categories of post-treatments: HT, ST, and MT. Subsequently, the specific treatments applied were identified, as well as the outputs investigated. In detail, three main outputs, such as tensile properties, surface roughness, porosity, etc., were considered to evaluate the effects of the post-treatment processes. Figure 2a reports an overview of the main categories of post-treatment processes adopted in the analyzed papers. Figure 2b, instead, shows the specific techniques and their frequency.

2.1. Heat Treatments

2.1.1. Aging Treatment

The AM metal parts possess a unique microstructure and residual stresses. Therefore, conventional heat treatments are often applied to homogenize the microstructure and reduce these stresses, in addition to tailoring the overall material properties [25]. Heat treatments are the most frequent and effective techniques used to overcome the limits of the MEX/M parts, as shown in Figure 2a. In detail, based on the current literature, the "aging" treatment covers ≈50% of the post-

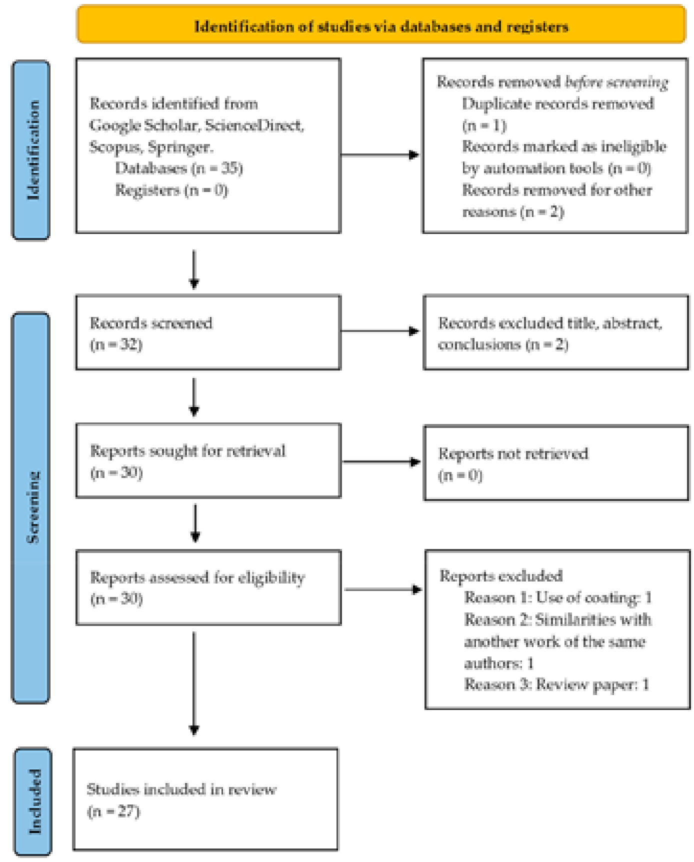


Figure 1: Flow chart according to PRISMA guidelines [24].

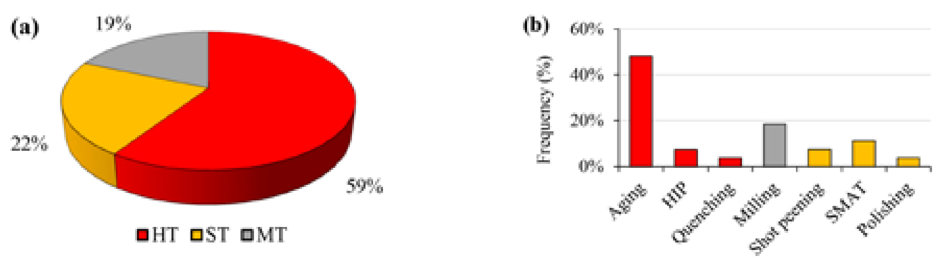


Figure 2: (a) Pie chart of the main post-treatment processes adopted. (b) Specific post-treatment processes mentioned in the analyzed papers. The colors of the bars are derived from the pie chart. HIP refers to hot isostatic pressing and SMAT refers to surface mechanical attrition treatment.

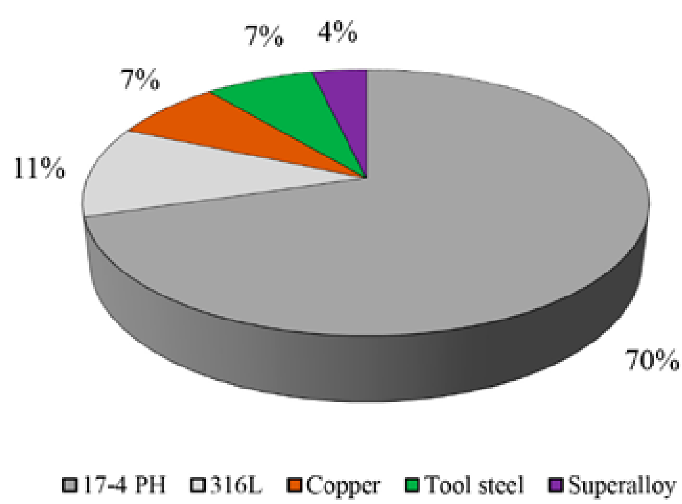


Figure 3: Materials under investigation for post-treatment processes on MEX/M.

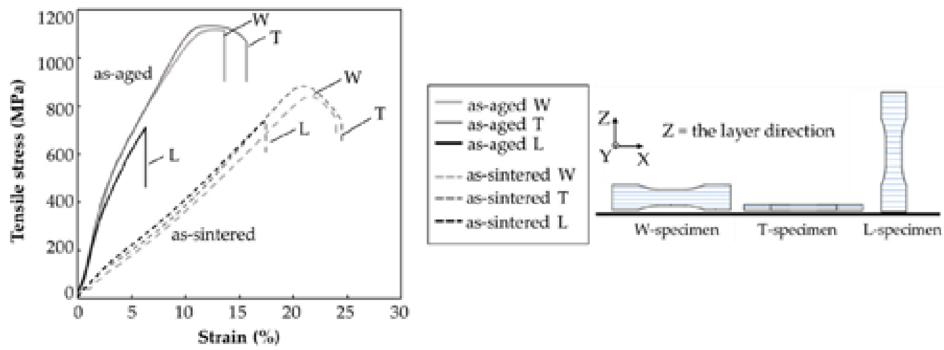


Figure 4: Tensile test curves in the as-sintered condition and the aged one for the different printing orientations. W = on-edge, T = flat, and L = upright. Adopted from [25].

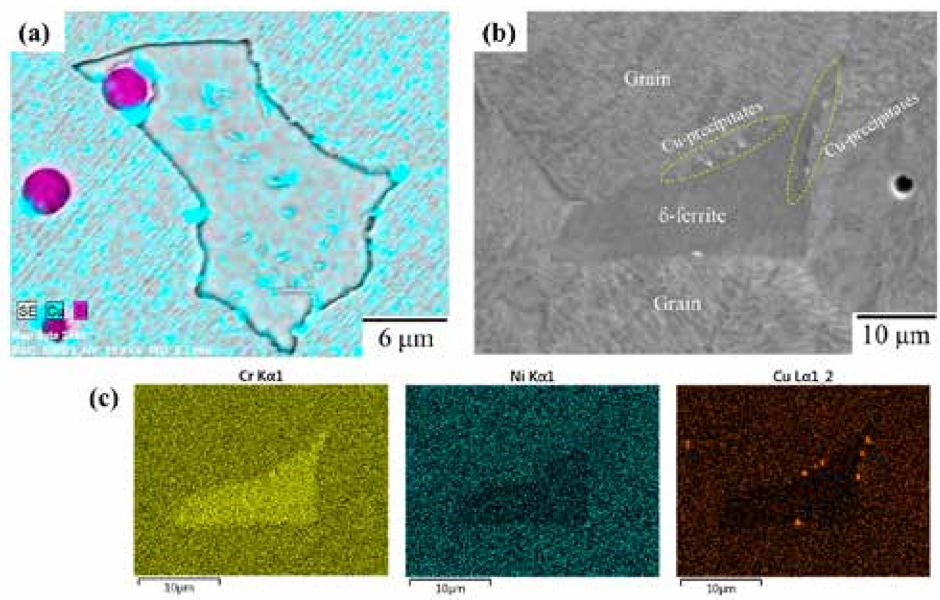


Figure 5: (a) Chemical mapping of copper and silicon on 17-4 PH that is H900-heat-treated [34]. (b) Image of microstructure of a 17-4 PH and (c) relative chemical maps [30].

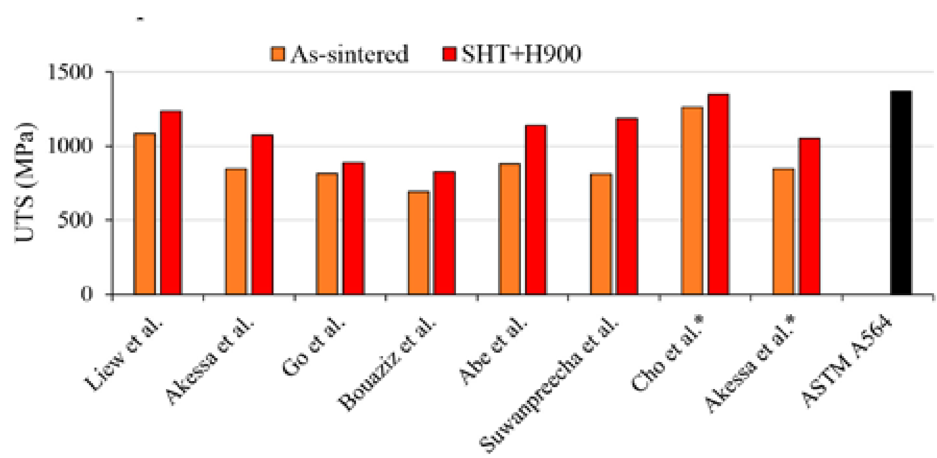


Figure 6: Comparison of UTS values after SHT + H900 for 17-4 PH stainless steel [13,21,26,27,28,29,31,35]. *refers to a cooling in water.

treatment processes adopted (see Figure 2b). Other heat treatments such as hot isostatic pressing (HIP) and quenching are less adopted. The predominance of aging is related to the availability of heat-treatable materials as feedstock for MEX/M, such as the precipitation-hardened martensitic stainless steel (e.g., 17.4 PH). Indeed, as reported in Figure 3, more than 50 percent of the works mentioning a post-treatment process refer to 17-4 PH stainless steel.

According to the relative standard ASTM A564 [26], aging treatments on 17-4 PH stainless steel are performed after a solutioning treatment (SHT) at 1,040°C for 0.5 to 1 hours. However, aging can be performed without prior solutioning, and in this case it is called "direct aging."

Abe et al. [27] and Bouaziz et al. [28] applied aging on 17-4 PH parts. In both works, the authors considered the H900 treatment (482°C for 1 hour) with a prior solutioning treatment and compared the properties of the as-sintered parts and the aged parts in terms of tensile properties. The H900 condition is named "peak hardening" condition because the highest values of tensile strength and hardness are reached. Indeed, according to the standard, the minimum tensile strength is 1,310 MPa, the minimum yield strength (YS) is 1,170 MPa, and minimum hardness is 40 HRC. Abe et al. [27] observed for different printing orientations (see Figure 4) an increase up to a maximum of 1,100 MPa of ultimate tensile strength (UTS) starting from a range of 840-880 MPa. At the same time, as expected, the aged parts became more brittle, with a significant decrease in elongation. Bouaziz et al. [28], instead, using the proprietary system ADAM, observed an increase in UTS of 16 percent in the aged parts compared to the sintered ones. Furthermore, the surface roughness was evaluated. A slight increase in average roughness (Ra) from 4.1 µm to 4.6 µm was obtained, possibly due to the thin external oxide layer generated on the surface after the HT.

Akessa et al. [29] investigated the response of 17-4 PH parts, varying the holding time (0 hours, 0.5 hours, or 1 hour) of SHT before the hardening stage H900 treatment and the cooling phase (air or water). Authors described a notable increase in UTS, up to 1,078 MPa, and in YS, up to 921 MPa, when the parts were solutioned at 1,038°C for 0.5 hours, aged and cooled with water. Indeed, cooling with water after H900 aging produced parts with a significantly higher YS compared to the parts cooled in air. In detail, YSs equal to 513 MPa (SHT time = 0.5 hours) and 602 MPa (SHT time = 1.0 hour) were observed for cooling in air, instead of 921 MPa (SHT time = 0.5 hours) and 892 MPa (SHT time = 1 hour) for cooling in water. However, the highest value of hardness (417 ± 29 HV) was recorded with prior solutioning for 1 hour and cooling in air. Another aspect often considered is the effect of the heat treatment on the residual porosity of the parts. Different authors analyzed how, after a specific heat treatment, the porosity in the parts changes. Pellegrini et al. [30] heat-treated 17-4 PH parts fabricated through different industrial extrusion-based technologies, such as ADAM, BMD, and traditional MEX filament-based technology. The H900 (482°C for 1 hour) and H1150 (620°C for 4 hours) conditions were adopted and investigated for their effects on hardness and porosity. The H1150 condition, referred to as "overaging," provides the highest ductility, accompanied by a corresponding decrease in hardness. Following the two aging treatments, hardness changed notably, particularly after H900, compared to H1150. More significant, however, was the effect on porosity. Indeed, the heat treatment reduced porosity from minus-1.5% to minus-34.3% compared to the as-sintered condition. Less significant were the differences in porosity observed by Go et al. [21] after SHT + H900. However, as observed also in the previous works, the mechanical response registered a significant increase in UTS (+9.3%), YS (+24.9%), and hardness (+17.6%), but also of the elongation (+26.7%).

Liew et al. [31] derived, from the aging treatment (H900 and H1150), interesting results relating to UTS (1,235 MPa) after H900, and to an elongation of 10.9% (≈+203% higher than the as-sintered condition) after H1150. These significant variations, as is widely discussed in the literature, are due to the enrichment of copper (Cu) precipitates in the matrix [30,32,33]. In Figure 5a and 5b, the matrix of 17-4 PH parts with a significant enrichment in copper can be seen. The tendency of Cu-precipitates to deposit on the grain boundaries emerged from the chemical mapping (see Figure 5b). However, when increasing the aging temperature and aging time, the Cu-precipitates tend to be coarse, favoring the increase in ductility. On the other hand,

Figure 7: Illustration of a HIP process. *The image was created through an AI assistant tool.

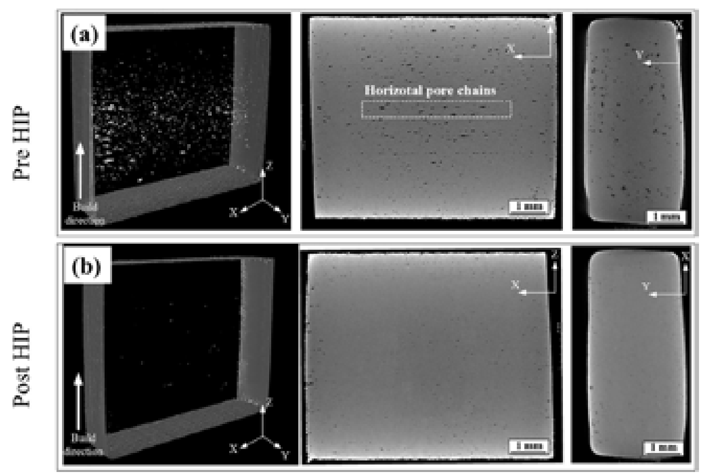


Figure 8: CT image of (a) as-sintered parts pre-HIP and (b) as-sintered parts post-HIP. Adopted from [34].

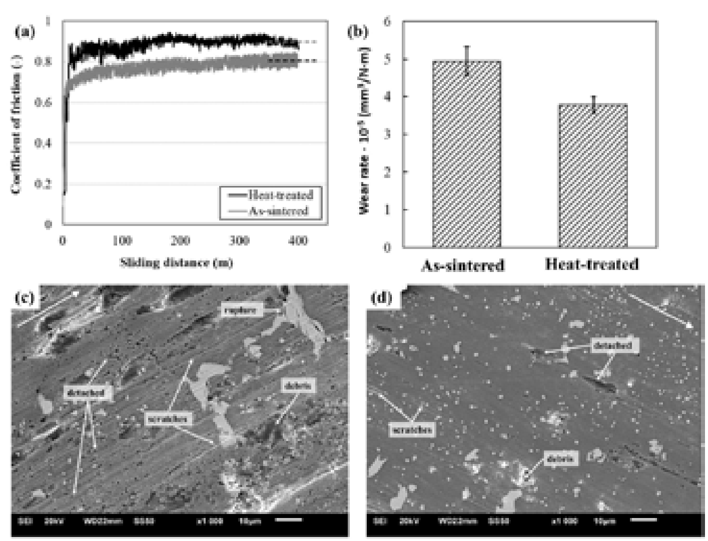


Figure 9: (a) Coefficient of friction (CoF) comparison, (b) wear-rate values for as-sintered and heat-treated M2 samples, (c) wear track on M2 as-sintered, and (d) wear track on heat-treated M2. Adopted from [35].

authors [31] found a notable result related to the pitting corrosion resistance that increased with the aging treatment, compared to the as-sintered condition. In detail, when overaged, the highest pitting potential (E_{pit}) is achieved.

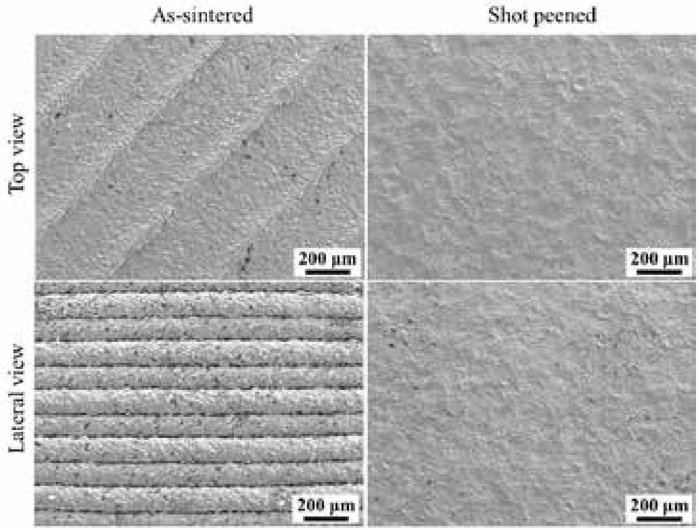


Figure 10: Scanning Electron Microscope (SEM) image of an as-sintered sample on top and lateral faces and a shot peened one. Adopted from [13].

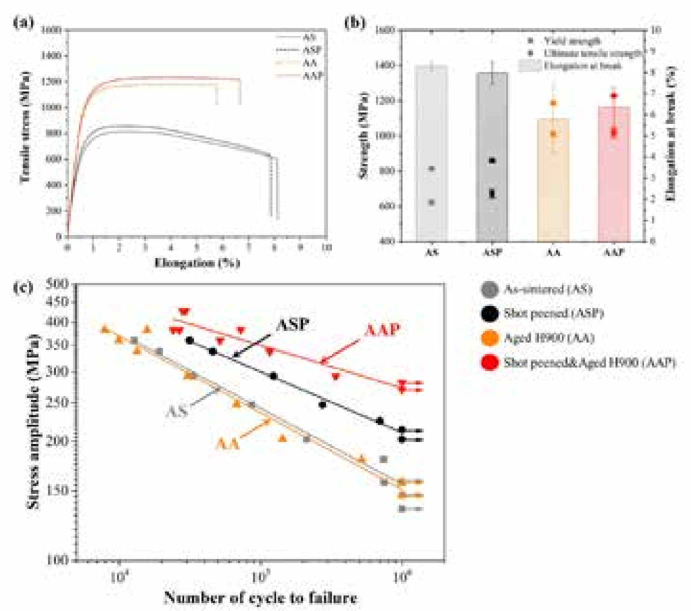


Figure 11: Results comparison of (a) tensile test curves, (b) tensile properties, and (c) fatigue test. Adopted from [13].

With the aim of making a comparison of the above mentioned results, Figure 6 reports the UTS achieved in the as-sintered on 17-4 PH parts after SHT + H900. Despite receiving the same post-treatment process procedure, notable differences were observed between the studies. Bouaziz et al. [28] reached the lowest UTS after SHT + H900 (825 MPa), despite Liew et al. [31] and Akessa et al. [29], using the same MEX/M technique (e.g., ADAM), reaching 1,235 MPa and 1,075 MPa, respectively. In the same way, in the work of Go et al. [21], the differences between as-sintered and aged were minimal (≈9.3%). In this case, a different sintering procedure, due to the different feedstock, can alter the result of the aging process. Finally, as observed in [29], when water was used as cooling agent, a notable increase in strength was achieved due to the rapid cooling of the quenching and the arising of the martensite phase.

Similarly, Forcellese et al. [34] exploited the intrinsic corrosion characteristic of the 17-4 PH material to understand how heat treatment can affect the localized corrosion resistance. Different printing orientations were investigated (orthogonal, parallel, and 45° with respect to the printing bed). Authors observed how the 17-4 PH parts realized through BMD increased their corrosion resistance properties thanks to the heat treatment that favored the growth of the chromium-rich ferritic phase, improving the localized corrosion resistance properties.

Finally, based on investigation of the literature, Thompson et al. [18] reported the effect of aging treatment on a nickel-based alloy and, in particular, Inconel 718. Nickel-based alloys are heat-treatable as a PH martensitic stainless steel. In detail, a typical heat treatment for the superalloy consists of a solutioning at 980°C for 1 hour, air cooling and subsequent aging at 720°C (8 hours) and 620°C (8 hours) in air to tailor the microstructure, favoring the precipitation of niobium precipitates. Compared to the previous works on 17-4 PH, residual porosity remained in the parts, but a significant enhancing of the mechanical performance after the aging treatments was observed.

2.1.2 HIP and Other Heat Treatments

Hot isostatic pressing (HIP) is a well-known heat treatment fundamental to consolidating metal powder, increasing density, and reducing porosity [23]. Generally, the process involves placing the part in a high-pressure furnace and subjecting it to both high temperature and uniform pressure from an inert gas such as argon (see Figure 7).

HIP is a crucial process for AM metal parts thanks to its capability to reduce porosity occurring during the manufacturing process. In this context, HIP for sinter-based processes such as the MEX/M can have a pivotal role. Nevertheless, the literature reports few examples about the use of HIP on MEX/M parts. Wang et al. [36] applied HIP for the first time on 316 L parts fabricated via MEX. As expected, the most significant result was in terms of porosity. Indeed, the authors decreased the porosity from 7.5 percent in the as-sintered parts to 0.3 percent in the HIPed parts, as reported in Figure 8a and 8b, respectively. Therefore, the reduction in porosity suggested an improvement in the mechanical properties, such as the tensile ones. Indeed, the UTS increased from 412 MPa to 540 MPa (+31%).

Ajjarapu et al. [15] analyzed the effects of the HIP process on pure copper parts. As for the previous work, the HIPed parts achieved a density of 97.7 percent, leading to higher UTS (+10%), higher elongation (+40%) and a higher Young's Modulus (+100%).

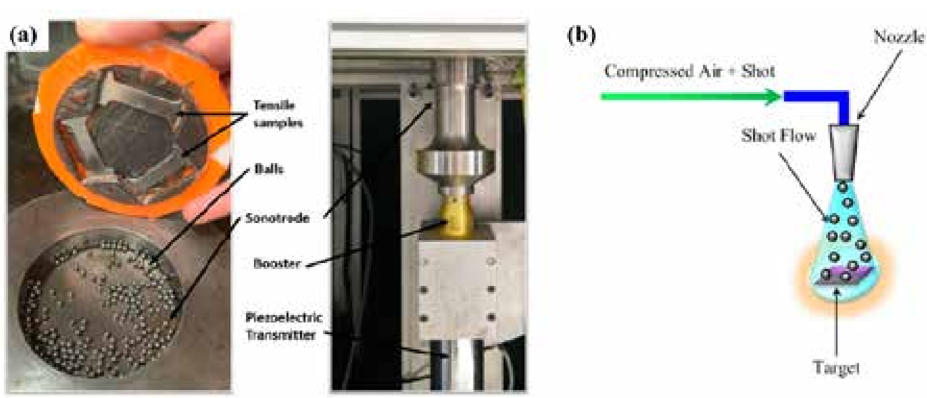


Figure 12: (a) Representation of SMAT [38] and (b) shot peening process [22].

Furthermore, the authors evaluated the intrinsic properties of copper such as the electrical conductivity, pre- and post-HIP. A dramatic increase in the electrical conductivity, close to 100 percent of IACS (International Annealing Copper Standard), was achieved thanks to the higher densification provided by the HIP process.

From Figure 2b, other heat treatments, such as quenching, have been less extensively investigated for metal parts fabricated via MEX. Generally, quenching is employed to increase the hardness of the metal through rapid cooling in water, oil, or gas. To reduce the brittleness introduced by quenching, a subsequent tempering step is often performed to enhance the toughness of the metal.

An example is reported by Naranjo et al. [37] on M2 tool steel produced through MEX technology. The authors heated MEX parts up to 1,180°C and performed oil quenching in the first step, followed by tempering at 525°C in a secondary step. They highlighted the benefits of heat-treating the parts, noting that the microstructure became more homogeneous, with a phase transformation from austenite to martensite and an enrichment of carbides, which resulted in increased hardness. Hardness in the as-sintered condition was ≈45 HRC and moved up to ≈62 HRC after the quenching and tempering cycles. Finally, the authors analyzed the tribological properties of the as-sintered and heat-treated parts. M2 tool steel, indeed, is often adopted in highly complex working conditions. The heat-treated parts showed better tribological properties than the as-sintered counterparts thanks to a higher hardness that generated a higher coefficient of friction (CoF) and a lower wear rate (see Figure 9a and 9b, respectively). The wear effects on the surfaces for an as-sintered sample (Figure 9c) and a heat-treated one (Figure 9d) are reported.

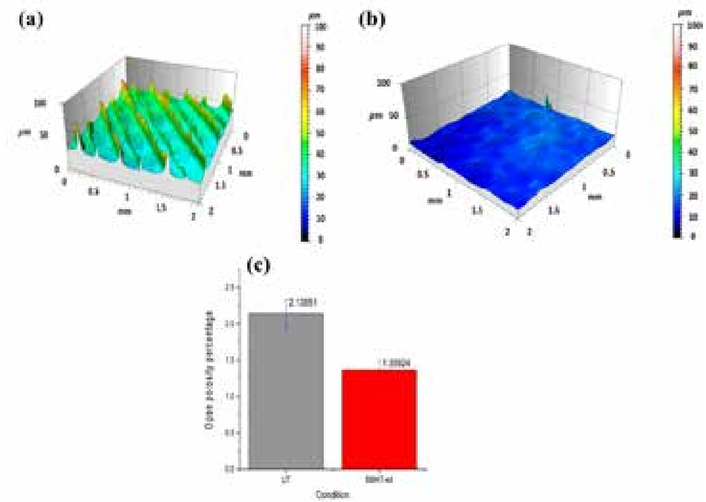


Figure 13: Three-dimensional profile of sample in (a) as-sintered condition and (b) SMAT condition. (c) Comparison between as-sintered and SMATed sample in terms of open porosity. Adopted from [40].

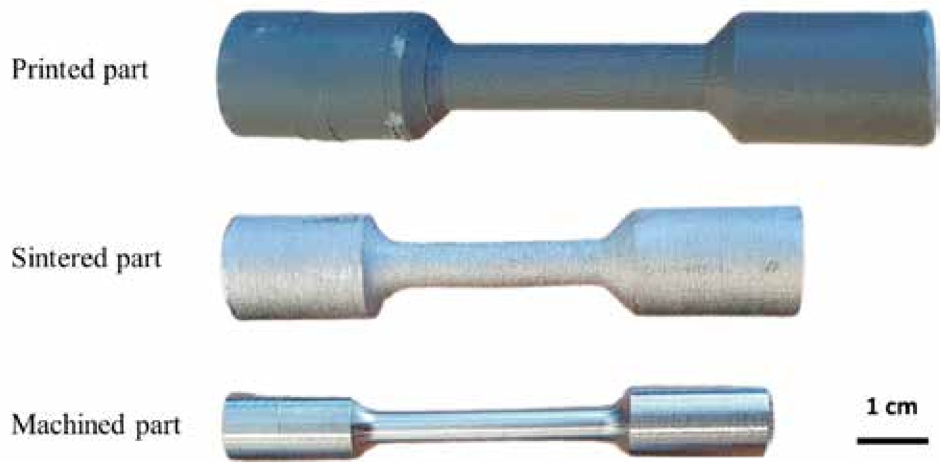


Figure 14: Fatigue test sample after printing, sintering, and machining. Adopted from [12].

2.2 Surface Treatments

Regardless of the extrusion mechanism, the parts realized through MEX suffer from a poor surface quality due to the layer-wise effect generated by the deposition of layer upon layer. Indeed, the wrong choice of some printing parameters can influence the outer surfaces, generating undesired voids the deposited strands or between layers. As for the other metal AM technologies, a rough surface, especially along printing orientation, can potentially affect the parts' response by reducing the application window of the produced parts. In this context, surface post-treatment processes appear to be the best solutions to overcome these limitations. Various surface post-treatment processes have been applied to the metal parts fabricated in AM. However, considering the MEX/M, this area is still unexplored. In Figure 2a, the papers related to the surface post-treatment are only 16 percent of the total, and when including machining technology as well, the total is lower than 40 percent. The modification of the surface properties of MEX/M parts is performed exclusively through mechanical treatments. In detail, it is requested that a tool (e.g., cutting tool, media, or granules) with determined characteristics, deforms, removes, or finishes the material surface (Figure 10).

Based on Figure 2b, shot peening, surface mechanical attrition treatment (SMAT), and polishing were the adopted processes. In this section, the machining is excluded from the discussion because it will be discussed more deeply in a dedicated section.

A significant contribution to this topic was proposed by Suwanpreecha et al. [13]. In their work, they showed how different post-treatment processes can affect MEX parts' characteristics. In

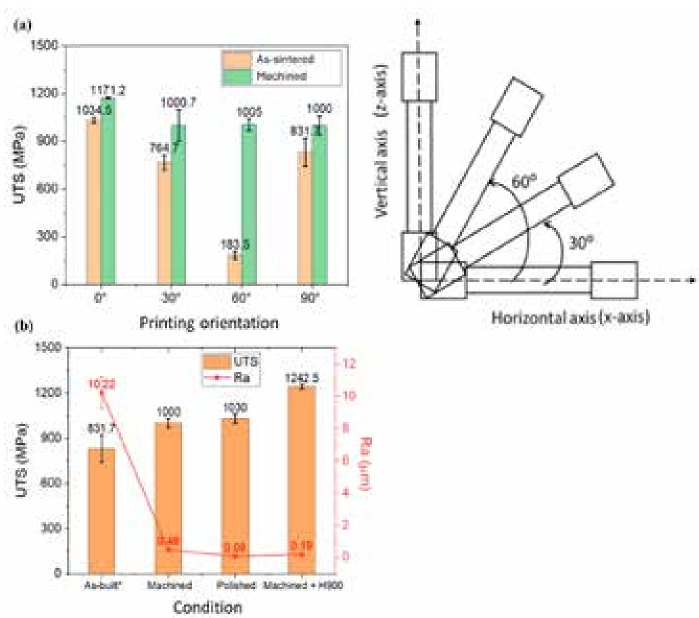


Figure 15: (a) Comparison of UTS values for the different printing orientations in as-sintered condition (orange bar) and machined condition (green one). (b) 90° printing orientation: UTS and Ra values for the different conditions. Adopted from [43].

Post-Treatment Process	Specific Process	Analyzed Surface	Ra Initial [μm]	Ra Final [μm]	ΔRa (%)	Reference
MT	Milling	n.d.	6.45	0.08	−98.8%	[14]
MT	Milling	Lateral	13.52	2.48	−81.7%	[44]
MT	Milling	Lateral	10.22	0.48	−95.3%	[43]
ST	SMAT	n.d.	0.39	0.04	−89.7%	[39]
ST	SMAT	n.d.	4.10	0.46	−88.8%	[38]
ST	Shot peening	Lateral	15.80	3.40	−78.5%	[13]
	Shot peening	Top	6.60	2.90	−56.1%	
ST	Shot peening	Top	2.42	1.95	−19.4%	[41]
ST	Polishing	Lateral	10.22	0.08	−99.2%	[43]

Table 1: Comparison of surface roughness values for different post-treatment processes.

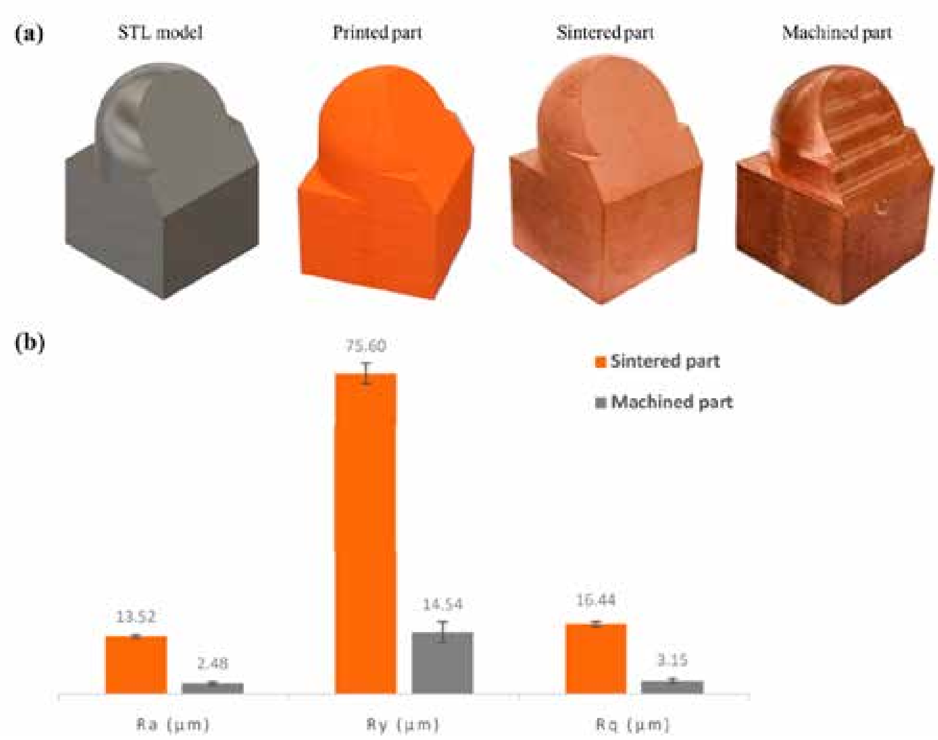


Figure 16: (a) Different stages of the methodology. (b) Roughness parameter comparison (as-sintered vs. machined). Adopted from [44].

detail, the authors used a shot peening process on 17-4 PH samples and evaluated different outputs such as surface roughness, tensile properties, and fatigue strength. The comparison for the top surface and lateral surface between the as-sintered and shot-peened samples is reported in Figure 10. The shot peening process removed any potential characteristics of MEX parts. Indeed, the typical layer-wise effect (lateral view) was completely removed, and the deposited strands were absent. In this context, the surface roughness (Ra) decreased dramatically from 6.60 ± 0.84 μm to 2.90 ± 0.14 μm on the top faces and from 15.80 ± 1.00 μm to 3.40 ± 0.30 μm on the lateral faces. Furthermore, the reduction in surface roughness allowed the sample to obtain a slight increase in tensile properties (+5.6% in UTS, +7.9% in YS) and significant improvement in fatigue strength (+46.2%). However, the authors obtain the best UTS, YS values and fatigue properties when the samples were shot peened and aged as reported in Figure 11a-c. These findings suggest how a combination of two or more post-treatment processes can be the right way to overcome the defects of the parts and the technological limitations of MEX/M.

To improve the tensile properties and surface roughness of 17-4 PH parts, Chemkhi et al. [38] adopted the SMAT process, a variant of the shot peening process with a multitude of parameters. SMAT consists of the high-frequency vibration of spherical balls (see Figure 12a) that creates a nanocrystallized layer at the material surface. On the other hand, the shot peening process (see Figure 12b) is a cold-working process that uses a stream of small shots to affect the material's surface. Chemkhi et al. [38], through SMAT, observed a notable increase in UTS from 500 MPa to 700 MPa (+40%), along with a remarkable reduction (≈90%) in the roughness measured on the top faces. The notable increase in the UTS appeared to be strictly related to the reduction in Ra and potential superficial defects that can generate crack initiation in the part. Indeed, the multiple shots that impact on the surface increase the hardness of the material, induce compressive residual stresses [22], and modify the grain size. All these characteristics typical of a surface mechanical treatment can enhance the mechanical response of the parts. Gong et al. [39], similarly, applied the SMAT technique on 17-4 PH samples and investigated its effects under mechanical loading. Firstly, the UTS tended not to vary; instead, the elongation of the SMATed samples reduced due to the hardening of the material (from ≈2.6% to ≈2.1%). Significant results, instead, were observed in the surface porosity. Indeed, SMAT reduced the pore content on the surface, also known as "open porosity," and their size in the initial stage under load (about 1.5 percent of strain). More than 1.5 percent of the strain, the pores closed through SMAT reopened, and no differences between the as-sintered and the SMATed ones are observed. Finally, a significant impact of the SMAT was observed in the deformation mechanism and crack propagation thanks to the reduction in superficial defects, pores, and surface roughness.

The SMAT process also appeared beneficial for the tribological and corrosion behavior of 17-4 PH parts. Indeed, the decrease in roughness (see Figure 13a, 13b) and the closing of the open porosities (Figure 13c) reduced the wear of the parts through abrasion and adhesion and at the same time avoided triggering of corrosion crevices. Naim et al. [40] indeed observed a reduced wear rate of the SMATed samples compared to the as-sintered ones. Furthermore, the corrosion properties, such as potential ($E_{corrosion}$), current ($I_{corrosion}$), and localized potential ($E_{localized}$) improved after SMAT.

As for the SMAT process, shot peening process parameters must be optimized to avoid undesired results. Hence, Suwanpreecha et al. [41] analyzed the effect of the shot peening time (5, 25, 50, and 75 minutes) on 316 L parts fabricated through BMD using hydroxyapatite as material media. After an initial decrease to 1.95 μm at 25 minutes, the Ra started to increase, becoming higher than the as-sintered condition at 75 minutes (2.57 μm vs. 2.42 μm). However, at the highest exposure time, the best results in terms of microhardness and tribological properties (coefficient of friction and wear rate) were obtained thanks to the induced work hardening mechanism of the post-treatment process.

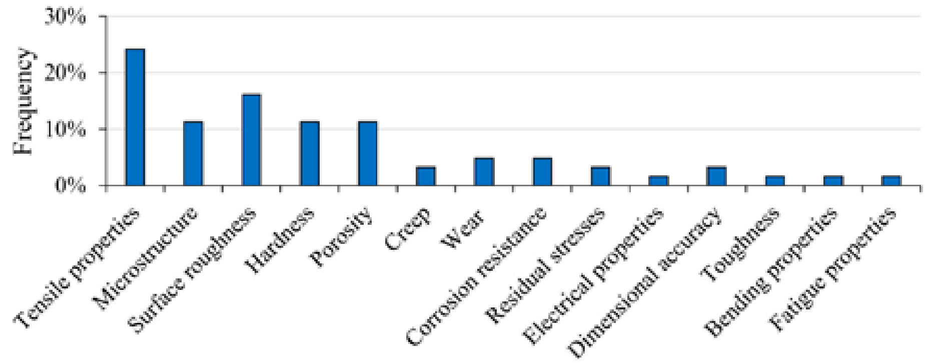


Figure 17: Analysis of the investigated properties based on the analyzed literature.

Post-treatment	Detail	Material	Target 1	Target 2	Target 3	Reference
HT	HIP	316 L	Microstructure	Porosity	Tensile properties	[36]
ST	SMAT	17-4 PH	Surface roughness	Tensile properties	Residual stresses	[38]
HT	Aging	17-4 PH	Tensile properties	Porosity	-	[27]
HT	Aging	17-4 PH	Tensile properties	Surface roughness	-	[28]
HT	Aging	17-4 PH	Hardness	Porosity	-	[30]
HT	Aging	17-4 PH	-	Tensile properties	Hardness	[43]
ST	Polishing		Surface roughness	-	-	
MT	Milling	17-4 PH	-	Tensile properties	Surface roughness	[13]
ST	Shot peening		Surface roughness	-	-	
HT	Aging		-	Fatigue properties	Tensile properties	
HT	Aging	17-4 PH	Creep	Hardness	-	[45]
MT	Milling	Tool steel	Surface roughness	Microstructure	Residual stresses	[14]
MT	Milling	Copper	Dimensional accuracy	Surface roughness	-	[44]
HT	Aging	17-4 PH	Microstructure	Corrosion resistance	-	[34]
HT	Aging	17-4 PH	Microstructure	Tensile properties	Corrosion resistance	[31]
MT	Milling		Tensile properties	-	-	
HT	Aging	17-4 PH	Tensile properties	Porosity	-	[46]
HT	Aging	17-4 PH	Microstructure	Tensile properties	Hardness	[29]
HT	Aging	Superalloy	Hardness	Toughness	Creep	[18]
HT	Aging	17-4 PH	Microstructure	Tensile properties	-	[35]
HT	Quenching	Tool steel	Wear	Hardness	-	[37]
HT	HIP	Copper	Porosity	Tensile properties	Electrical properties	[15]
HT	Aging	17-4 PH	Porosity	Tensile properties	Microstructure	[21]
ST	Shot peening	316 L	Surface roughness	Wear	Hardness	[41]
MT	Milling	316 L	Dimensional accuracy	Bending properties	-	[12]
ST	SMAT	17-4 PH	Tensile properties	Porosity	Surface roughness	[39]
ST	SMAT	17-4 PH	Surface roughness	Wear	Corrosion resistance	[40]

Table 2: Summary table of post-treatment process category and detail, material and main properties investigated for each author. HT (heat treatment), ST (surface treatment), MT (machine technology).

2.3 Machining Technologies

Machining technologies belong to conventional manufacturing (CM) processes, together with forging and casting. Despite AM technologies and CM technologies often having been considered alternatives to each other, their combination generated a new area of manufacturing called “hybrid manufacturing.” This hybridization consists of the adoption of CM technologies as post-treatment processes for parts manufactured through different AM technologies to satisfy geometric, dimensional, and surface quality requirements [42]. Indeed, computer numerical control (CNC) machines are commonly used to remove metal parts produced by laser-based technologies from the printing bed. In a subsequent step, the parts are reworked using CNC machining to eliminate typical defects resulting from the additive process. In the industrial landscape, DMG Mori AG (Tokyo, Japan) is the pioneer and leader company in the hybrid manufacturing area. On the other hand, in the last decade, the scientific community has deeply investigated this area, especially considering PBF-LB and DED-LB technologies.

Over the past five years, MEX/M has begun to adopt this hybrid approach. According to the available literature, milling is the preferred machining technique (see Figure 2b). In particular, CNC milling machines are employed for their high accuracy and repeatability, allowing the correction of manufacturing errors or achievement of the desired part dimensions.

CNC machining was adopted by Tecelli et al. [43] and Jansa et al. [12] in their respective works. Jansa et al. [12] adopted the CNC machining for each sample test, as reported in Figure 14. In addition, the authors observed how the machining provided significant improvements in the elastic modulus of the samples tested under a bending test (about two times) and in the flexural stress, which was about 8 to 11 percent higher than in the as-sintered condition.

Tecelli et al. [43] observed how the machined test samples reduced the initial surface roughness along the printing orientation (the most critical one) from 10.22 µm to 0.48 µm and enhance the UTS along each printing orientation as reported in Figure 15a, 15b. However, the improvement in Ra and UTS appeared lower compared to the machined and polished samples (0.08 µm and 1,030 MPa, respectively), but higher if compared when the samples are machined and H900 aged. These results confirmed the observation in [13] that the combination of the post-treatment processes enhances the properties of the MEX/M parts.

With respect to the previous work, Monzón et al. [44] reported an interesting approach for the hybrid manufacturing of MEX/M Cu-parts. The aim of their study was to provide an analysis of dimensional characteristics and surface characteristics of different types of test artifacts realized through ADAM technology. These parts belong to the standard ASTM 52902:2019. The process chain consisted of the printing, debinding, and sintering of the artifacts, subsequent analysis of the reduced dimensions after sintering due to the shrinkage, computation of the oversizing factors for machining process, and validation of the methodology. The results obtained allowed them to define the oversizing factors for a complex part in a hybrid manufacturing process chain (see Figure 16a). In Figure 16b, instead, the surface properties in terms of roughness (Ra, Ry, and Rq) were evaluated pre- and post-machining treatment, and an overall decrease ≈81% was obtained.

With respect to previous works, in the work of Kolomy et al. [14], the inadequate surface characteristics of the as-sintered parts were considered the main issue of the MEX/M parts for the industrial application fields. In this context, the authors reported a structured approach to define the best combination of cutting parameters for H13 parts fabricated through MEX/M and make the surface characteristics compliant to the strict industrial quality requirements. Cutting speed, feed per tooth, and cooling were considered tunable process parameters for their work. After several tests, authors identified 80 m/min, 0.005 mm/tooth and flood cooling as best combinations. Indeed, a significant low Ra was obtained (0.08-0.09 µm) and the microhardness of the machined parts increased +20% with respect to the as-sintered condition. However, the authors reported that using flood cooling along with the highest cutting speed and feed per tooth resulted in the highest compressive residual stresses in the samples. Conversely, dry machining produced slightly higher surface roughness (Ra = 0.08-0.10 µm) but lower compressive residual stresses.

The comparison of the effects of surface roughness for the investigated post-treatment processes is reported in Table 1. The analyzed surface is considered due to the evident differences that MEX/M parts show between the lateral faces and the top face. When the authors did not specify the surface of analysis, "n.d." is reported.

In summary, significant improvements were observed after each post-treatment process, with a final Ra value in the range of 0.08-2.48 µm after machining, 0.04-0.46 µm after SMAT and slightly higher after shot peening at 1.95-3.40 µm. Polishing, instead, allowed the achievement of a final Ra equal to 0.08 µm, with the highest percentage variation (ΔRa%) being equal to minus-99.2% with respect to the as-sintered condition. The ΔRa% was calculated as the percentage variation in Ra before the post-treatment process and after.

2.4 Summary of the Results

In this section, an overview of the analyzed and discussed papers is reported in Table 2. A representative graph of the main investigated properties is reported in Figure 17.

3 OUTLOOK AND INDUSTRIAL APPLICATIONS

MEX/M technology is still undergoing intensive investigation across all its main phases, as researchers continue to optimize processes and mitigate the well-known limitations that characterize multi-step technologies. The adoption of post-treatment processes is recognized as a necessary step to overcome the inherent limitations of the MEX/M process chain. While a sequenced approach of two or more post-treatments has been shown in a few studies to combine and amplify individual process benefits, this expansion directly conflicts with management factors such as production time and cost. Accordingly, the challenge for the combination of MEX/M and post-treatment processes lies in defining a critical balance between these technological benefits, the economic constraints, and the environmental impact of the process chain.

Furthermore, the analyzed literature suggests a significant shift in the scientific community's approach: Post-treatment processes are no longer seen as a separate, optional step but are now considered essential to making MEX parts industrially viable and competitive. This evolution is driven by the recognition that post-processing is a critical tool for enhancing material properties and quality. A more advanced trend is the development of "in-process treatments." Thanks to technological advancements and the integration of different enabling technologies, both industries and academia are exploring integrated manufacturing systems. Collaborative robots or other automated systems that combine the MEX printing process with a post-treatment step are under development or in the prototyping phase. This approach allows post-treatments to be implemented not as a separate workstation operation, but as a layer-by-layer, or quasi-layer-by-layer process, integrated into fabrication. In addition, in situ visual scanning systems able to monitor the deposited layers can further improve the industrial applicability of this technology.

4 CONCLUSIONS

The present review paper has dealt with the adoption of different types of post-treatment processes for metal parts realized through material extrusion (MEX/M). The adoption of post-treatment processes opens the possibility to enhance mechanical properties, tailor the microstructure, reduce the porosity, and improve the surface roughness. Based on the analysis of the available scientific literature, heat treatment, surface treatment, and machining are identified as the main post-treatments adopted. The predominance of heat treatment (they represent about 60 percent of the performed treatments on MEX/M parts) is strictly related to the characteristics of the feedstock material available for MEX/M, the easiness to perform, and the relevant impact on material properties. Surface treat-

ments are also commonly applied, and studies focused on enhancing surface finish and dimensional precision through machining play a key role in advancing hybrid manufacturing technologies. The implementation and optimization of hybrid processes enable the reduction or elimination of typical AM defects, while preserving their inherent advantages. Recently, considerable interest has emerged in these multi-step, integrated processes, which are effective in enhancing the performance of AM technologies. In this context, surface treatments and machining can be regarded as auxiliary techniques, even from an "in-process" perspective.

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DATA AVAILABILITY STATEMENT

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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During the preparation of this manuscript, the authors used Gemini, 2.5 Flash for the purposes of generating Figure 7, embedded in this article. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

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CONFERENCE PROFILE ///

WORLDPM

THE PRIMARY SOURCE FOR METAL POWDER TECHNOLOGY TRANSFER

Courtesy: Shutterstock

For the first time in six years, WorldPM will bring its additive manufacturing knowledge to North America.

By THERMAL PROCESSING STAFF

Powder metallurgy has become a crucial part of manufacturing in the thermal processing industry, not just in North America, but across the globe. That's why it's vitally important that workers in this field have the opportunity to gather in one place to discuss the latest trends and innovations in the powder metallurgical sector.

For years, the WorldPM conference has provided this service to the industry, and for the first time in six years, WorldPM will be in North America.

WorldPM, presented by the Metal Powder Industries Federation (MPIF), is the largest global powder metallurgy and particulate materials event of the year. On June 25-29, 2026, the PM industry will come together in Montreal, Canada, at, not only for WorldPM, but for two more conferences as well. These conferences will be sintered together into one global event. The other shows making up this hat trick of PM are AMPM2026 and Tungsten2026.

Montreal is a charming destination that is quickly becoming one of North America's leaders in cutting edge innovation — thanks to the booming tech scene powered by the city's creativity and affordability. Montreal is one of the top destinations in North America for international association conferences, according to the International Congress and Convention Association.

The WorldPM2026/AMPM2026/Tungsten2026 conferences are the primary source for metal powder technology transfer and is host to the largest annual North American exhibit showcasing leading suppliers of metal powders, particulate materials, and metal additive manufacturing (AM)/3D printing process equipment, powders, and products. This meeting is the premier conference in this field and will draw participants from industry, government laboratories, and academic institutions.

The conference will offer a plethora of innovative programs, including a keynote speech, oral and poster technical presentations, industry awards, and, of course, an exhibition filled with companies demonstrating new concepts and equipment.

AMPM2026 is the leading technical conference focusing on metal additive manufacturing in the Americas and is a hub for technology transfer for professionals from every part of the industry. AMPM2026 will feature worldwide industry experts presenting the latest technology developments in this fast-growing field.

Tungsten2026 is dedicated to tungsten, refractory, and hard materials in the Americas. This event serves as a vital platform for professionals across the industry to share knowledge and foster innovation. Tungsten2026 will feature leading experts presenting the latest advancements and research in this essential field.

To prepare for these important conferences, Thermal Processing has compiled highlights from the technical sessions that readers might find helpful in planning their WorldPM schedule:

FRIDAY, JUNE 26

» **A High-Performance Ni-based Superalloy for Extreme Environment Applications.** Harikrishnan Rajendran, The Boeing Company. ATI 1700$^{(TM)}$ is a high-performance, nickel-based superalloy engineered to enhance the performance of additively manufactured components for extreme environments. The alloy delivers exceptional strength at temperatures approaching 1,800°F, outperforming many other nickel-based superalloys suitable for additive manufacturing, and demonstrates resistance to strain-age cracking and corrosion as validated during the Boeing DOE-ARPA E HITEMMP program. While initial development focused on additive manufacturing routes, we have expanded the effort by consolidating ATI 1700$^{(TM)}$ powder via hot isostatic pressing and further refining the microstructure through various thermomechanical processes. Preliminary mechanical testing of these PM variants across multiple temperatures has been completed and ongoing testing aims to provide a detailed comparison between powder metallurgy and additively manufactured properties. The efforts support qualification of PM ATI 1700$^{(TM)}$ for extreme environment structural applications.

» **Influence of Sintering - Homogenizing Conditions and Rapid Cooling on Microstructure and Properties of Sinter – Hardened PM Parts.** Ravindra Kumar Malhotra, Malhotra Engineers. Sinter-Hardening process is a combination of PM Primary process of sintering and secondary process of hardening. Conventional hardening via homogenizing in controlled atmosphere and oil quenching after completing sintering needed two separate furnaces, which cause bottlenecks. The advent of sinter-hardening steels gave sinter-hardening process for PM parts needing subsequent hardening in one furnace with special cooling features utilizing same protective sintering atmosphere. The result of the sinter-hardening process is dependent on different sub processes such as lubricant removal, pre-sintering, sintering, and homogenizing prior to rapid cooling and post cooling. There will be influence of cooling rates achieved during rapid cooling coupled with alloy customization for desired part properties. There is a role of sintering fixtures too which may hinder with free cooling as a tradeoff for maintaining critical dimensions or flatness. Limitations of multilayer loading reduces sinter-hardening outputs as compared to normal sintering from the same furnace. A dream sinter-hardening furnace would work with similar process parameters as would a normal sintering operation from the same furnace giving identical throughputs. The only difference should be high-low running of the cooling blowers as per design. Comparison of set of sintering parameters and thermal profile with end results on sinter-hardening parts would be an in-depth review of process equipment design and powder to achieve best results of microstructure and properties of PM parts for demanding applications with rated life cycle.

» **Reactive Liquid-Phase Sintering of TiB_2-MoB_2 Ceramics.** Jhewn-Kuang Chen, National Taipei University of Technology. Titanium diboride (TiB_2) is a promising ultra-high-temperature ceramic for aerospace and defense applications due to its high hardness, thermal stability, and electrical conductivity; however, poor sinterability and intrinsic brittleness limit its practical use. Molybdenum diboride (MoB_2) exhibits improved sinterability and toughness but reduced hardness when used alone. In this work, a reactive liquid-phase sintering strategy was employed to fabricate TiB_2-MoB_2 ceramics at a relatively low temperature of 1,550°C. Optimized compositions exhibited refined microstructures and reduced porosity, achieving a maximum relative density of 94.2% for $Ti_{0.5}Mo_{0.5}B_2$. The highest hardness of 22.5 GPa was obtained for $Ti_{0.75}Mo_{0.25}B_2$, while a balanced mechanical performance of 323.4 MPa flexural strength and 8.9 MPa·m$^{0.5}$ fracture toughness was achieved. Toughening mechanisms include crack deflection, grain-boundary pinning, and liquid-phase-assisted densification. Density functional theory calculations confirm enhanced metallic bonding from MoB_2 dissolution into the TiB_2 lattice, contributing to improved toughness and ductility.

» **Retained Austenite Formation and Its Impact on Mechanical Properties of Sinter-hardened and Heat-treated Low Alloy Steels.** Amber Tims, PMT, North American Höganös Co. Martensitic transformation is a primary objective for sinter-hardenable and heat-treated powdered metal (PM) materials. Equally important is the stabilization of austenite within the metallurgical matrix at room temperature. Retained austenite can significantly influence impact strength, ductility, and fatigue resistance of PM components. It can also detrimentally affect dimensional stability and hardness due to its inclination to transform to bainite or martensite when subject to thermal variations. Therefore, precise control over the quantity of retained austenite is essential for optimizing both wear performance and impact resistance in these materials. This paper will evaluate various sinter-hardened and heat-treated alloys to assess the relationship between retained austenite and mechanical properties and the effect of tempering conditions.

SATURDAY, JUNE 27

» **Active HIP Atmospheres - The Next Lever for HIP Processing.** Anders Magnusson, Quintus Technologies. When using Hot Isostatic Pressing (HIP) to optimize the reliability of mission-critical components in aerospace, medical, energy, racing, etc., an inert gas pressure medium is typically preferred to avoid introducing unknown variables to the process. Due to this, inert, high-purity argon is the standard gas for transmitting pressure and heat from the system to the processed components. The most common exception to this rule is for densifying nitride materials such as silicon nitride where nitrogen gas is used to prevent the nitride from dissociating at the high temperatures required for sintering and full densification of the material system. However, outside these two main HIP atmosphere scenarios, the use of specific atmosphere gases in the HIP system is generally considered experimental. Several specific applications have historically been explored with varying success, including active carburizing atmosphere for case hardening or for retaining alloy carbon, using partial pressure oxygen to stabilize oxides, or to use a nitrogen atmosphere for pressure assisted nitridation case hardening. The latter has, due to recent advances in clean-HIP processing, proven to be a promising candidate for the in-situ creation of a wear-resistant surface on, for example, medical implants needed for both increased wear resistance and as diffusion barrier for metal ions leaving the implants provoking metal hypersensitivity. Building upon these possibilities, this paper takes a further look into the integration of process steps that enhance both productivity and component properties within the HIP cycle.

» **Transferred Arc Plasma - Wire Atomization of Refractory Metals.** Joseph Tunick Strauss, HJE Company, Inc. Processing of refractory metals via additive manufacturing enables the production of parts with refractory metal properties in shapes not attainable by any other manufacturing method. For laser and e-beam AM processes, this requires that the refractory metal be available as powder with a spherical morphology. Current production of spherical refractory metal powders includes conventional non-transferred arc plasma atomization, EIGA-type and plasma melted gas atomization, and plasma spheroidization of nascent powders. Past studies have shown that transferred arc plasma-wire atomization has the potential to process conventional materials (i.e. stainless steels) while operating at a lower specific energy consumption. This paper presents the preliminary trial results of processing W, Mo, and Ta via transferred arc plasma-wire atomization.

» **Optimization of Sinter-Brazing Process Parameters for Repeatable High-Strength Joints for Mass-Produced Complex PM Components.** Sudarshan Palve, Egearz Pvt Ltd. Sinter-brazing is an efficient technique for assembling multiple complex components together. A combination of sintering and brazing into a single thermal cycle enables efficient joining of complex components with reduced process time and cost. However, achieving consistent brazed joint quality, mechanical strength, and controlled dimensions of the components is challenging. This paper presents a systematic approach to improve the sinter-brazing process by optimizing key parameters such as RM selection, atmosphere control, thermal profile, and joint design. Experimental trials were conducted using modified furnace parameters, improving wetting behavior to enhance brazed-joint integrity. Advanced characterization techniques including metallography and breaking load performance evaluation were used to assess the effectiveness of the improvements. The optimized process demonstrated significant enhancements in bond strength with improved dimensional stability and repeatability. The outcome of this study provides a practical framework of a robust and efficient sinter-brazing process.

» **Grain Growth Control by Niobium Additions in Cryomilled and Spark-Plasma Sintered Aluminum Alloys.** Mathieu Brochu, McGill University. Niobium additions were investigated as a way of preventing excessive grain growth by pinning grain boundaries during sintering in nanostructured aluminum alloys. Two Al-Nb powders and one Al powder were cryomilled, annealed, and spark-plasma sintered, followed by characterization using X-ray diffraction and electron microscopy to determine grain size and other microstructural changes during processing. It was found that small niobium additions were effective in avoiding grain growth without modifying sintering behavior, while alloys containing higher amounts of niobium were more difficult to densify because of their increased strength at high temperature.

SUNDAY, JUNE 28

» **Compact Vertical Furnace for Iron Powder Reduction and Annealing:** Minimum Floor Footprint, Maximizing Energy Efficiency Using Low Reaction Gas and Ensuring Uniform High-Quality Output. Ravindra Kumar Malhotra, Malhotra Engineers. Reduction and annealing of iron powder in a vertical furnace will improve powder quality as compared to a conventional horizontal sheet-belt furnace. In a horizontal furnace, the reducing gas hydrogen or cracked ammonia passes over a powder bed of fixed height with limited penetration through powder particle spaces. As the reduction and annealing process takes place, there is particle-to-particle bonding commonly known as cake formation. In a vertical retort, the powder is completely filled, allowing reducing gas to pass through the space between all powder particles. In the vertical furnace, gravity-and-screw-feeder-assisted powder movement has inherent attrition taking place. This attrition would not allow particle-to-particle bonding or cake formation. Slight vibration can further increase attrition, therefore powder will have more space for gas movement and better oxide reduction of each iron particle. The retort will be heated by cylindrical embedded heaters giving uniform heating around the retort. The four-zone (84kW) furnace will have 3 cylindrical heaters per zone (21kW). The hot shell height can be controlled below 5 meters. The cooling system will also have cylindrical jackets of SS and MS covering a height of less than 4 meters. Spiral path water flow within each jacket will be metered separately. This will ensure the adjustable cooling rate to control powder properties. The design temperature of this furnace will be 1,000°C for iron powder.

With this setup, different furnaces can handle a variety of process cycles of powders on the shop floor. This furnace should give outputs of about 8-10 tons per day.

» **Integrated Production of High-Purity Copper Powder via Novel Vertical Continuous Chip Oxidation and In-Line Reduction for Precision Sintered PM Components.** Ravindra Kumar Malhotra, Malhotra Engineers. A novel vertical continuous oxidizer processes machining chips (0.5-3mm) or shredded fine copper wires in to high surface area input for replacing traditional mill-scale used in production of submicron reduced copper powder by pulverization-reduction process. Conventional mill-scale a by-product of copper extrusion process has refractory fines and oils as contaminants. This new method using a vertical oxidizer will eliminate any such impurities. There is a distinct advantage in using this method to convert non-usable coarse powder from a water atomization plant into a premium powder grade. The loss-making recycling of coarse powder in melting can be diverted as good input for reduced powder production upscaling. The sheet belt reduction furnace used in the plant can handle both powder types, atomized as well as reduced. The dryer section of the reduction furnace can be used for preheating copper scales before reduction and then annealing. The improvised reduction muffle will have hot nitrogen curtains in the beginning and end. The reduction hydrogen or cracked ammonia gas also will be preheated. Reduction and annealing sections will be separated by a reverse parabolic baffle for gas dam. This will ensure reduction side gas will not diffuse in annealing gas thereby purity of reduced powder will be enhanced. The cooling jackets with controlled spiral path water flow will give uniform cooling. Additional nitrogen gas curtains in the cooling jackets will protect powder cake color and purity needed for precision PM parts.

» **Effect of Supersolidus Liquid Phase Sintering Conditions on the Bonding of Particles, Microstructure, and Mechanical Properties of AlSi10Mg Alloy.** Julien Moreau, École de Technologie Supérieure. This study investigates the effect of supersolidus liquid phase sintering conditions on AlSi10Mg powder bonding, microstructure formation, and the resulting mechanical properties of the samples. Sintering was conducted in the 550-579°C range with a holding duration of 2 hours. The sintering included heating (varied between 5 or 15 hours) and cooling (varied between 12 or 70 hours). All thermal cycles — heating, cooling, and sintering dwell — were performed under a nitrogen atmosphere. The result indicates that higher sintering temperatures and faster heating/cooling rates lead to a lower fraction of AlN. In contrast, lower sintering temperatures or slow heating promoted the development of a thicker AlN shell around the powder particles. This shell inhibited the bonding of the powder and prevented densification via the sintering process. Sintering in the 571-579°C range, with heating during 5 hours, constitutes a more favorable window for the densification of AlSi10Mg under a nitrogen atmosphere. At 571°C, the alloy exhibits fine Al grains and small Si particles uniformly distributed within the Al matrix, resulting in high hardness. At 575°C, grain coarsening and partial coalescence of Si particles occur, leading to a reduction in hardness. At 579°C, grains become larger, while Si evolves into elongated structures that surround the Al grains, improving overall hardness. After T6 heat treatment, Si particles and Al grain structure remain stable; however, the hardness nearly doubles due to precipitation strengthening.

» **A Double Sand-Sealed Electric Kiln with Inconel-Sheet Fabricated Retort for Production of Reaction-Sintered and Nitride-Bonded High-Strength Silicon Carbide Parts.** Ravindra Kumar Malhotra, Malhotra Engineers. A double sand-sealed 21 kW kiln with a fully welded Inconel-sheet fabricated retort has been designed for 1,250°C temperature. The three cubic feet (retort volume) kiln under construction is for trials of reaction-sintering processes, especially nitride-bonded high-strength silicon carbide parts. Nitrogen gas is needed above 1,200°C for silicon-nitride formation from silicon powder to be use as bond for silicon carbide molded, compacted or vibration cast parts being sintered. Nitrogen or any other process gas is released inside the retort base itself. A ceramic monolithic precast block with well distributed holes has been engineered to cover the entire charge area. Uniformly spent gas and binder vapors are led out of the retort using a vent pipe of suitable height and diameter to increase dwell time of heated reaction gas inside the retort. This gas dwell penetrates the green compacts to complete the nitriding reaction without any air ingress from any part of the kiln. The outer surface of the circular retort is electrically heated uniformly as per the desired ramping cycle selected in the kiln monitoring system. The start and end of process reaction gas flow is interlocked as per the gas reaction time needed. Suitable kiln furniture is designed for the parts to be sintered. Green parts can be powder compacted, slip cast, or 3-D printed. Even a single large 3-D printed part can be reaction-sintered. The retort can be removed to increase kiln volume for non-critical work using single sand-seal of the kiln body. The electric terminals of the kiln are kept gas tight using suitable gland packing technique.

MONDAY, JUNE 29

» **Novel Multi-Burner Exothermic Lubricant Removal System with Metal Roof Embedded Heating for High-Throughput Mesh-Belt Iron PM Sintering Furnaces.** Ravindra Kumar Malhotra, Malhotra Engineers. Exothermic gas fired lubricant removal systems employing multiple burners are commonly used for iron-based powder metallurgy (PM) parts in mesh-belt furnaces. The air-to-gas ratio of each burner is adjusted for many purposes: lubricant combustion, generation of exothermic gas, and green part heating. In the balancing act of firing for heating and exo-gas production, there is a mismatch. The roof shape and its gap from charge is critical for functioning of the exothermic delube system. Introduction of a metal roof instead of refractory blocks improved sintering results significantly. Embedded electric heaters in the roof would reduce heating load of burners. This change will stabilize exo-gas production. Uniform top radiation heating of green parts from metal roof will make this system robust and easy to operate. New hybrid lubricant removal systems will improve carbon control, part density, and surface finish of heavy multi-layer sintered parts.

» **Effect of Vacuum Conditions on the Densification and Chemical Composition of Sinter Based Additively Manufactured Ti-6Al-4V.** Giorgio Valsecchi, TAV Vacuum Furnaces SPA. Sinter based additive manufacturing (SBAM) technologies offer a cost-effective alternative to conventional methods for producing complex titanium geometries. However, the thermal processing of reactive metals like Titanium Grade 5 (Ti-6Al-4V) presents severe metallurgical challenges. The material's high affinity for interstitial elements, specifically oxygen, nitrogen, and carbon at elevated temperatures necessitates rigorous atmospheric control to prevent alpha-case formation, embrittlement, and loss of ductility. This study investigates the critical role of sintering atmosphere by processing MoldJet fabricated Ti-6Al-4V green parts under distinct conditions including high vacuum, medium vacuum, and controlled partial pressures of argon. Comprehensive analysis of the sintered samples included Archimedes density measurements, interstitial chemical analysis, and mechanical testing. The study aims to define operational windows that minimize interstitial contamination, providing the data necessary to optimize the trade-off between component quality and production costs.

EDITOR'S NOTE This article was compiled and edited from the WorldPM website at www.worldpm2026.org.

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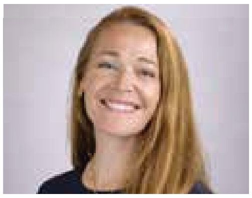

AMANDA LUCAS /// TECHNICAL WRITER

KIMBERLY UPTON /// INDUSTRIAL ENGINEER /// TORMACH

“When we have a more diverse team, it creates an opportunity to build products that apply to a wider range of people.”

What are your roles at Tormach?

Amanda Lucas: I’m a technical writer. I create and maintain all of the customer-facing instructional material like operator manuals, installation guides, release notes, and then the safety labeling that’s on the product. A big part of my role is to take the complex or technical procedures and write them in a way that’s clear and understandable to everyone.

Kimberly Upton: I work in our supply chain, and i have a degree in industrial engineering. I do a combination of planning and sourcing, but I also perform other duties like assembly instructions and routings and project management. I wear a lot of hats and also coordinate with other departments.

Why is it important to diversify these traditional roles in industry?

Lucas: I actually find it beneficial that I don’t have an engineering background because I think I can approach the user-interfacing content from a different perspective than the people who were developing the product. If we all had the same background, it would be easy to make assumptions about what the end user already knows.

Upton: I was taught through my education and experience the importance of understanding the various facets and roles that support manufacturing. Having that background makes it possible to work with various departments and with people of different experiences.

How are manufacturing roles becoming more cross-functional while blending engineering, operations, and communication?

Lucas: From my perspective, I’m bringing the documentation in earlier in the product cycle release so that it isn’t the last thing we’re thinking about. That helps me to work with engineers and support operations. It also helps me to not only understand how something works, but also how it’s actually used in the field.

Upton: The ability to wear many hats means understanding and being empathetic to what other people are doing in their roles and their jobs and to be able to soften those edges of the silo, so you’re able to work within the other departments and also question things.

Do you see the industrial landscape changing at a positive pace or do you still see a lot of opportunity for improvement?

Lucas: I feel encouraged to see the industry changing with regards to more women and younger generations getting into STEM fields. The opportunity there is converting that interest into long-term careers in the field.

Upton: I’m noticing that there are more women in important roles, like leadership. Personally, I see this as a huge benefit. Not only do women tend to have more empathy, flexibility, and support for employees, but it shows other women that these roles are possible.

Do you see the barriers not as high and more obtainable?

Upton: I am noticing a positive change. Women are sticking with their engineering jobs and roles; there seems to be more flexibility, support, and acceptance in the workplace.

Lucas: I don’t really see many barriers to entry and getting your foot in the door, but there is a need to create workplaces where more women or more diverse populations would want to apply to or could work and could see themselves long-term.

How are companies missing out on opportunities that would be advantageous to them by diversifying traditional roles?

Lucas: When we have a more diverse team, it creates an opportunity to build products that apply to a wider range of people. If we’re bringing people into the company who could evaluate and give their opinions on products early in the life cycle of the development, then you know we have a better chance to create a product that more people will want to use.

Upton: If you have a diverse set of employees, you’re going to be more well-rounded in how you are coming up with an idea and putting that product out for a customer.

How do you change the way decades-old companies approach their hiring paradigm?

Lucas: It starts with recognizing that adjacent skill sets have value and not just the traditional engineering. On the hiring side, they can offer a workplace that can attract a wider range of people. Maybe that’s things like flexibility and remote work, benefits packages that support a different range of lifestyles and life situations that people might have. That could make a big difference in widening the scope of who is able to enter the workplace and stay in the workplace.

Upton: Flexibility and support are crucial. That didn’t exist 20 years ago with a lot of the companies I worked with. I have a lot of friends who I graduated with who no longer do engineering, and it was because of the lack of flexibility and support.

There’s a plethora of very well-educated smart women out there who would gladly come back to the work environment if they knew of the flexibility and support that existed. It’s a golden nugget out there that hasn’t yet been found.

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