VOL. 18 NO. 1 SPRING 2024

FOR THE MIM, CIM AND SINTER-BASED AM INDUSTRIES

PIM INTERNATIONAL

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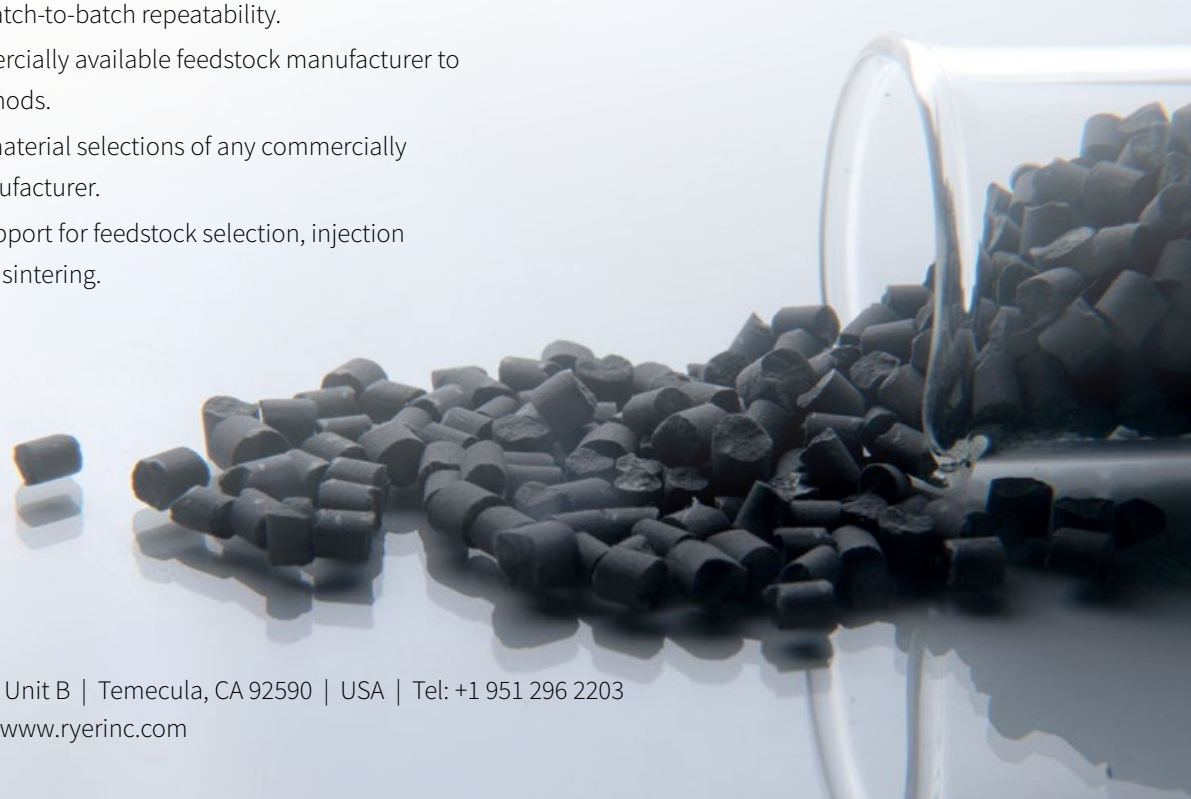

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Design and production
Inovar Communications Ltd.
ISSN: 1753-1497 (PRINT)
ISSN: 2055-6667 (ONLINE)
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FOR MIM, CIM AND SINTER-BASED AM

PIM INTERNATIONAL

A focus on advances in Ceramic Injection Moulding and ceramic AM

The Ceramic Injection Moulding industry can look ahead to growth on multiple fronts. To quote Dr-Ing Tassilo Moritz in a past issue of *PIM International*, "ceramics are in vogue as never before."

Cool to the touch with unrivalled aesthetic properties and a scratch-resistance that keeps the most elegant products looking like new forever, the technology has found a home in the luxury goods sector.

Yet, the technology is also thriving for industrial and medical applications. When all other materials fail – turn to ceramics. From their wear and corrosion resistance to their biocompatibility, ceramics excel in numerous areas.

This is not so say, however, that the technology rests on its laurels. In this issue, three articles shine a light on the supply chain for ceramic feedstocks, innovations in Ceramic Injection Moulding that promise enhanced quality, capability and productivity, and, lastly, the manufacturing of multi-material functionally graded ceramics via Additive Manufacturing.

If you picked this issue of *PIM International* up at one of the many ceramic exhibitions this Spring, why not keep in touch – follow us on Linkedin or sign up to our newsletter at www.pim-international.com.

Nick Williams
Managing Director & Editor

Cover image
The most important piece of equipment in ceramic feedstock production: the shear roll extruder (Courtesy INMATEC)

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- Learn the benefits of binder jetting technology, which requires no expensive lasers and prints at high speeds
- Explore how binder jetting is similar to long-trusted Metal Injection Molding (MIM) processes
- Review details on final part density and quality of binder jetted parts
- See the incredible flexibility for printing stainless steels, nickel-based alloys, and other metals, including aluminum, titanium, and copper
- Read about customers using Desktop Metal systems

Download the Guide at

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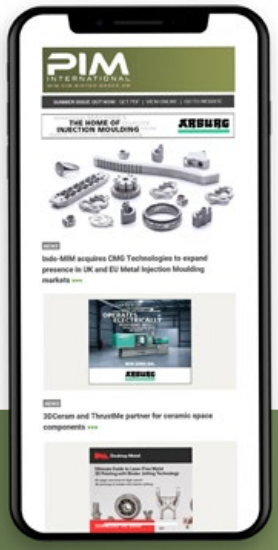

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Industry News

To submit news for inclusion in *PIM International* contact Paul Whittaker: paul@inovar-communications.com

3DEO secures investment from Seiko Epson and Development Bank of Japan

3DEO, headquartered in Los Angeles, California, USA, has announced a significant investment from the Development Bank of Japan Inc. (DBJ) and Seiko Epson Corporation (Epson), reported to total around one billion yen ($6.8 million). According to *Nikkei Asia*, Epson and DBJ participated in a funding round that involved existing investors and, while the full details have not been disclosed, the investment made by the two Japanese companies was believed to account for a roughly 5% stake.

"The collaboration with DBJ and Epson is a powerful endorsement of our mission to empower product and engineering teams across the globe," stated Matthew Petros, CEO and co-founder of 3DEO. "This investment is not just capital; it's a commitment to a shared vision of challenging what's possible through the combination of additive design principles and differentiated capabilities."

In Japan, there is a strong belief in conventional metalworking based on precision casting, which has supported the growth of the machining and assembly industry, as well as the optimisation of the supply chain in terms of quality and cost. However, while there is a movement toward research and development of AM technologies and DfAM, the adoption rate at production sites faces significant barriers. This collaboration is poised to address these challenges, contributing to the advancement of AM technologies within Japan's established manufacturing landscape.

DBJ and Epson's investment, secured after careful review by the Committee on Foreign Investment in the United States (CFIUS), will enable 3DEO to leverage the Japanese manufacturing industry's strengths while fostering technological advancements in both regions.

"By integrating 3DEO's AM capabilities with the meticulous engineering tradition of Japan, we aim to unlock new levels of productivity and expand the manufacturing possibilities in one of the world's leading economies," added Payman Torabi, CTO and co-founder of 3DEO. "This investment is a testament to the trust and potential seen in 3DEO's innovative approach. We are excited to collaborate with DBJ and Epson, leveraging their expertise and market reach to enhance and refine the landscape of Additive Manufacturing."

Founded in 2016, 3DEO is an AM service bureau using its in-house patented process it calls Intelligent Layering. The technology is a fusion of Binder Jetting (BJT) and CNC machining that 3DEO claims is faster, cheaper and capable of higher resolution than BJT alone. 3DEO's unique AM process, and its advanced Design for Additive Manufacturing, is underpinned by a differentiated portfolio of eighteen patents.

www.corporate.epson
www.dbj.jp/en
www.3DEO.co

3DEO received a 2023 MPIF Award of Distinction for this fastener assembly used to attach the inter-car baffles to retaining frames on bullet trains (Courtesy MPIF)

Lithoz sees record year with its ceramic AM machine sales rising by 30%

Lithoz GmbH, located in Vienna, Austria, has reported a record year of growth for its ceramic Additive Manufacturing business, achieving a 30% increase in machines sold and nearly doubling material production compared to 2022.

A key focus for Lithoz has been the launch of the Ceramic AM Factory, which uses the company's Lithography-based Ceramic Manufacturing (LCM) Additive Manufacturing machines for industrial mass production. With a majority of machines this year having been sold to partners with multiple Lithoz systems, serial production has been noted as a 'clear contributor' towards Lithoz's record results.

Lithoz has marked a record year of growth based partly on the expansion of serial Additive Manufacturing (Courtesy Lithoz)

"By establishing these interconnected machine parks, Lithoz is driving the growth of serial production in ceramic 3D printing," stated Dr Johannes Homa, Lithoz CEO. "We're working consistently with our customers to scale up to mass production. With one of our partners now producing well over one million parts per year, it's fantastic to see all the effort paying off!"

Alongside serial production, Lithoz has focused on developing an 'all from one source' portfolio of ceramic Additive Manufacturing solutions. This approach has seen investments into Laser-Induced Slipcasting technology, LSD-Print and Multi Material Jetting (MMJ) via AMAREA Technology.

In 2024, Lithoz has reported that it intends to further support the growth of ceramic Additive Manufacturing by increasing the number and strength of service bureaux worldwide. By establishing machine parks and broadening its offering of ceramic AM solutions, Lithoz intends to advance the Ceramic AM Factory for serial mass production and drive forward industrial applications.

www.lithoz.com

Desktop Metal announces $50M savings plan and 20% workforce reduction

Desktop Metal, Inc., headquartered in Burlington, Massachusetts, USA, has announced a cost-saving plan of $50 million that includes a 20% reduction in its workforce. The move is said to be part of a broader strategic business review aimed at improving its profitability. Other actions include continued consolidation of facilities and product rationalisation.

"The cost-reduction plans announced today, in addition to the $100 million in cost reductions realised in 2023, will help us generate positive cash flow in light of a softer demand environment," stated Ric Fulop, founder and CEO of Desktop Metal. "We are committed to getting profitable during this challenging period. The vast majority of the cuts will be completed this quarter, resulting in sequential cost reductions across the first half of 2024."

"While our industry is working through a challenging period, Desktop Metal's commitment to its Additive Manufacturing 2.0 vision has not changed. We continue to have a positive long-term outlook for this industry as it transitions to mass production," Fulop continued.

Desktop Metal has notified US-based employees impacted by the cuts. The company is continuing to review modifications to its international workforce, the timing of which will be subject to local regulatory requirements.

This recent action is anticipated to lead to pre-tax restructuring charges of $24.3 million to $31.5 million. The majority of these expected charges are non-cash, with around $5.3 million to $7.5 million of the restructuring charges coming from cash reserves.

Desktop Metal said it is continuing to invest in products and operations in line with near-term revenue generation, positioning the company to achieve its long-term financial goal of sustainable profitability.

The company will provide further details about these changes in its regulatory filings and end-of-year earnings release and conference call, which is expected by the end of March 2024.

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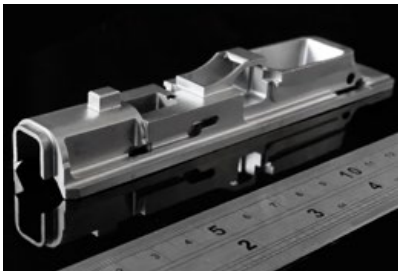
Calls for EIB to allow defence-related investments; MIM offers path to ramping up EU firearms production



MIM firearms part produced by Spain's Ecrimesa, one of many European companies with expertise in supplying the firearms industry

The European Parliament has approved a resolution calling on the European Investment Bank (EIB) to abolish restrictions on financing ammunition and weapons production, in a bid to ramp up security-related expenditure in response to the continuing conflict in Ukraine, reports Euroactiv. The move has the potential to boost investment in the region's Metal Injection Moulding capacity. MIM is a key technology for firearms production that, prior to Russia's invasion of Ukraine, already accounted for almost 20% of European MIM sales by value.

The EIB's current mandate is reported to limit the range of permissible defence-related investments to so-called 'dual-use' technologies, which can be used for civilian and military purposes. According to the Bank's lending criteria, most of the technology's expected future revenue must derive from its civilian use. This also means the bank is currently explicitly prohibited from investing directly in ammunition, weapons, and 'core military and police infrastructure.'

The vote was held on the same day that the EIB president, Nadia Calviño, is reported to have told a plenary session of the European Parliament that the bank would "step up" its "support for European industry in the areas of security and defence." Calviño also told MEPs that the EIB will engage with the European Commission and other stakeholders on the "definition and scope" of dual-use technologies.

The bank will also attempt to accelerate the deployment of the €6 billion in funds that remain available under the bank's 2022 Strategic Europe Security Initiative (SESI), of which €2 billion has already been invested in drone technology, cybersecurity, and border security.

European Commission President Ursula von der Leyen was reported to have told MEPs that she was "very encouraged by the words of President Calviño that the EIB is ready to do more to contribute to joint projects that boost the European defence industry." ■

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ORNL and Lithoz partner to process non-oxide ceramics for high-temperature applications

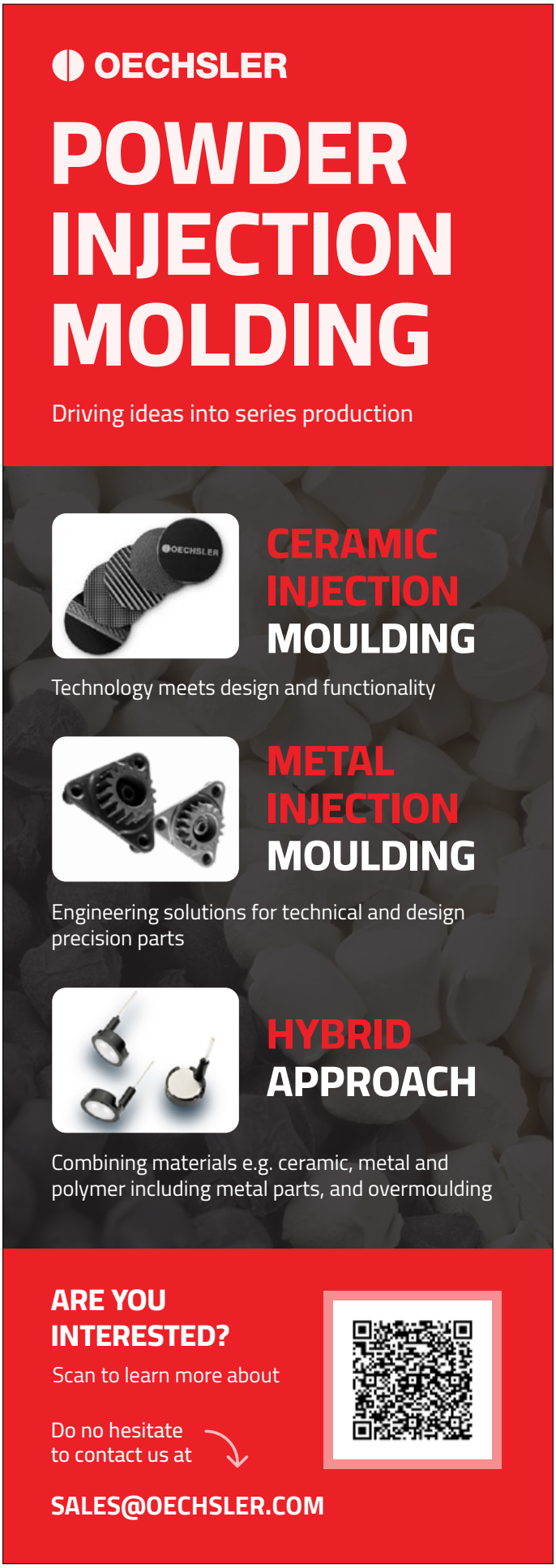
Lithoz GmbH, located in Vienna, Austria, has signed a Cooperative Research and Development Agreement (CRADA) with the US Department of Energy's (DOE) Oak Ridge National Laboratory, Tennessee. The collaboration will explore high-temperature ceramics processing via the use of Lithoz's Additive Manufacturing technology to advance the processing and manufacturing of non-oxide ceramics.

Based on Laser-Induced Slipcasting (LIS) technology, the Lithoz AM machine uses laser slurry drying, or net shaping, technology to guide computer-controlled light amplification by stimulated emission of radiation to desiccate liquid-suspended controlled layers of solids. The aim of the cooperative agreement is to further develop this technology to shape non-oxide ceramics with high-refractive indexes, such as silicon carbide, for use in extreme temperature applications.

Lithoz's LIS technology can reportedly produce parts with more complex geometries and larger scales than traditional moulding techniques allow. By incorporating intricate inner channels and complex designs, the parts it can produce are lighter and more efficient when compared with current methods. This technology is also capable of increasing the range of materials that can be used by processing dark ceramics, such as silicon carbide and silicon nitride, in a way that is unachievable with other processes.

"This project will build on ORNL's years of research in developing and testing high-temperature materials and ceramics," stated Corson Cramer, Extreme Environment Materials Processing Group staff scientist at ORNL. "By combining our expertise with Lithoz 3D printing capabilities, we have the potential to change the concept of high-temperature ceramics processing for heat exchange, aerospace and defence applications."

www.lithoz.com
www.ornl.gov



Kymera International acquires copper-based powder producer Royal Metal Powders

Kymera International, a speciality materials company headquartered in Raleigh, North Carolina, USA, has acquired Royal Metal Powders Inc., a manufacturer of water and air-atomised copper-based powders located in Maryville, Tennessee.

Under the continued leadership of Mike Lutheran, president of Royal Metal Powders, Kymera will continue operations at Royal's facility until all production can be moved to Kymera's manufacturing sites in North Carolina, Pennsylvania and Germany. It was added that Lutheran will be joining Kymera as Senior Vice President.

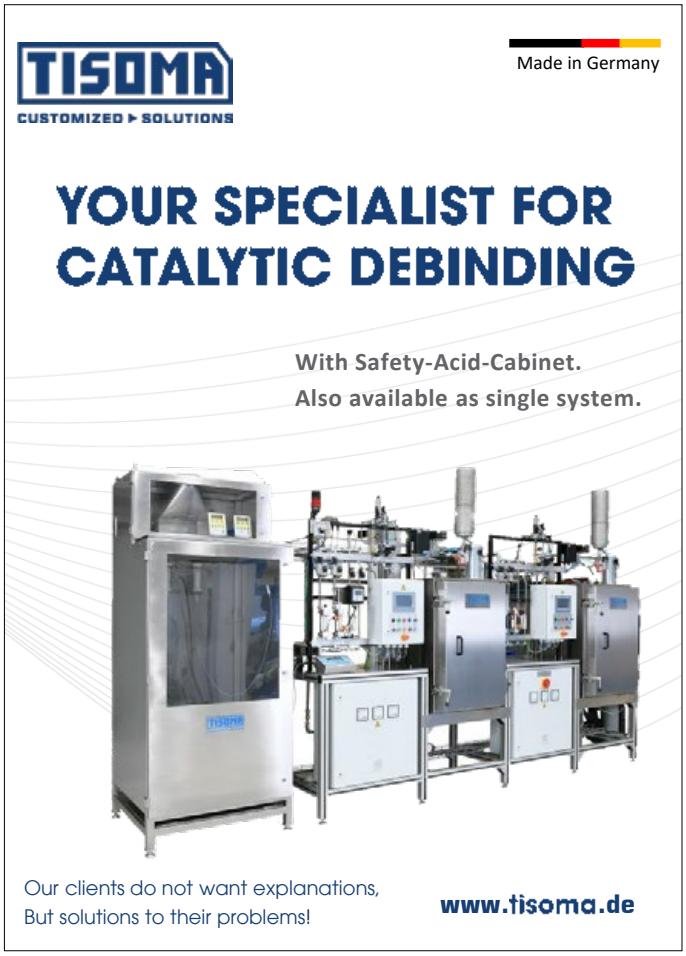
"The copper powder markets have encountered headwinds over the past few years, but we remain committed to ensuring Kymera and Royal's customers receive timely and high-quality supply of these critical materials for decades to come," stated Barton White, CEO of Kymera. "As demonstrated by our recent $20 million expansion of our North Carolina facility, Kymera is positioned to provide uninterrupted, long-term supply for the entire market."

Royal Metal Powders will continue at its Maryville facility until production can be moved to Kymera's existing facilities (Courtesy Kymera International)

Royal Metal Powders offers a wide variety of powders, including copper, brass, premix and pre-alloyed bronze powders, nickel/silver, tin powder, electrolytic copper powders, lead powders, and phos copper powders.

Adam Shebitz, Partner at Palladium Equity Partners, the parent company of Kymera International, added, "We are pleased that Kymera continues to demonstrate its unwavering commitment towards the copper powder market. Following the recent expansion undertaken at Kymera's RTP facility, the acquisition of Royal's assets reinforces Kymera's position as a well-capitalised and high growth supplier of niche specialty materials."

www.kymerainternational.com
www.royalmetalpowders.com



Thomas Weissgärber elected co-chair of the European Powder Metallurgy Institute

The European Powder Metallurgy Institutes (EPMI), a Sectoral Group of the European Powder Metallurgy Association (EPMA), has announced Prof Dr-Ing Thomas Weissgärber as co-chair of the EPMI Working Group alongside Adj Prof Dr Dr habil Susanne Norgren. Weissgärber takes over from Prof Elena Gordo following the end of her four-year term in the position.

The EPMI is an association of twenty major European PM research centres. Under the umbrella of the EPMA, the experts support and promote cooperation between industry & research and advocate relevant policies on education and research topics in the field of PM.

Thomas Weissgärber is Director of Fraunhofer IFAM Dresden and has held a professorship in Powder Metallurgy at Technische Universität Dresden since April 2022. He has published over 200 articles and had involvement in over eighteen patent applications. In 2018, he won the Skaupy Prize and, in 2022, the EPMA Fellowship Award.

www.epma.com

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Bodycote completes Lake City takeover, ends Stack deal, announces £60M share buyback programme

Bodycote plc, headquartered in Macclesfield, Cheshire, UK, has, completed its previously announced acquisition of Lake City Heat Treating (HT), Warsaw, Indiana, USA. The company also announced that it had ended the agreement to acquire Stack Metallurgical Group, based in Albany, Oregon, due to a failure to satisfy all closing conditions to the agreement.

Lake City HT is a prominent Hot Isostatic Pressing (HIP) and vacuum heat treatment business, primarily supplying the orthopaedic implant market as well as civil aerospace. The move is expected to significantly increase Bodycote's customer reach in the medical market.

The consideration paid on closing for Lake City HT was $66.5 million on a cash and debt-free basis. After expected tax benefits worth approximately $7.5 million, the net price paid was $59 million. Lake City HT is forecasted to have achieved 2023 full-year revenues of around $14 million, with operating profit expected to be around $6 million. The business achieved 30% revenue growth in 2023 and is expected to continue to deliver good progress.

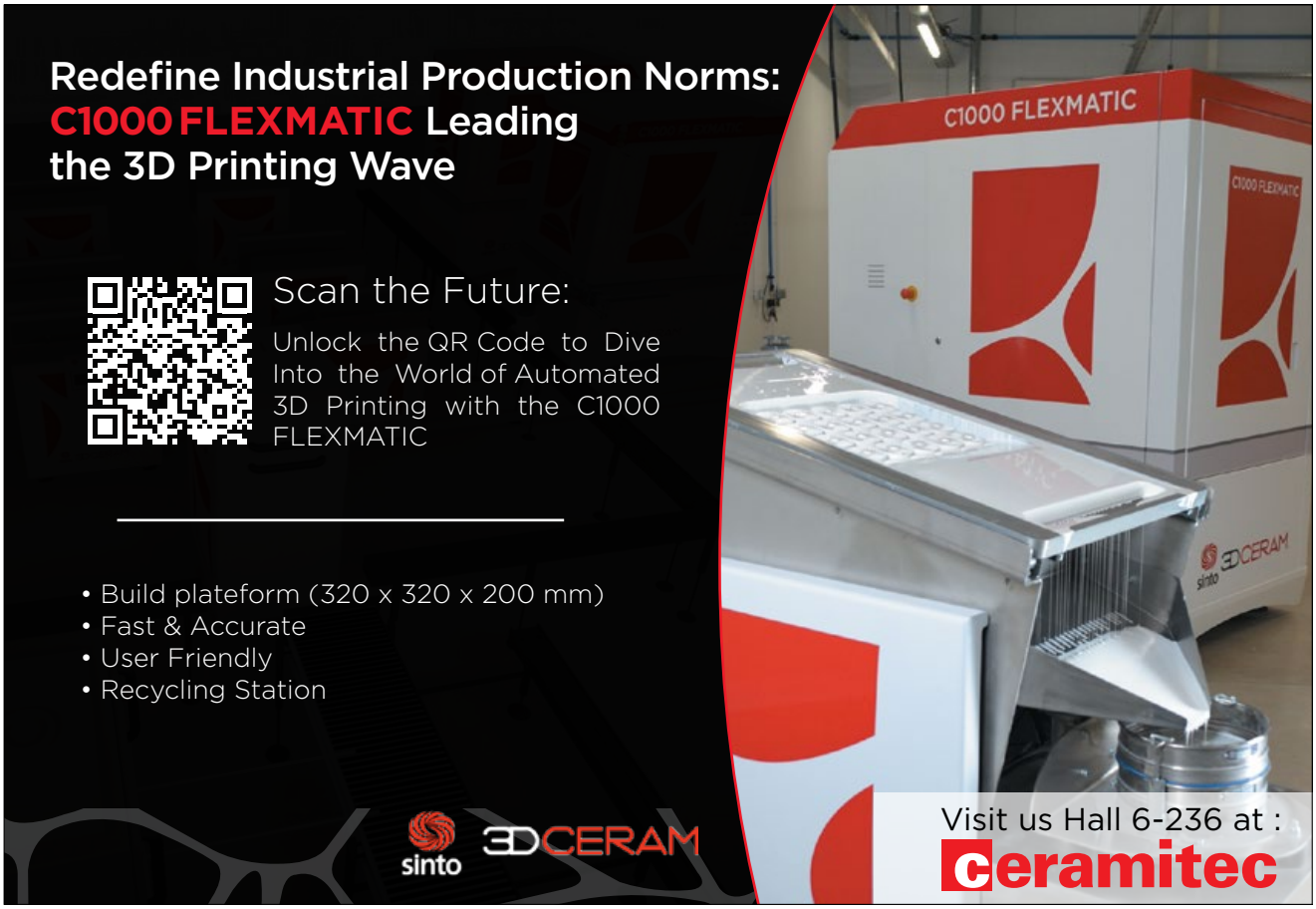
"Completion of the acquisition of Lake City HT is an exciting further step in our strategy to grow our Specialist Technologies businesses and footprint," stated Stephen Harris, Group Chief Executive of Bodycote plc. "This acquisition is an excellent fit, enhances our profitability and earnings per share in addition to allowing us to capitalise on the appealing structural growth opportunities in medical and aerospace markets."

£60 million share buyback programme

Bodycote also reported that, in light of the lower-than-anticipated acquisition spend, the group's strong balance sheet and balanced approach to capital allocation, it has announced the intention to launch a share buyback programme of up to £60 million. The share buyback programme is expected to commence on March 18, 2024.

"The share buyback programme represents an attractive use of our capital," Harris continued. "It highlights the strength of the group's balance sheet, together with our commitment to a balanced and disciplined approach to capital allocation to drive growth and shareholder value."

www.lakecityheattreating.com
www.bodycote.com



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Lithoz expands multi-material Additive Manufacturing with investment in Amarea Technology

Lithoz GmbH, based in Vienna, Austria, has announced that it has made a strategic financial investment in Amarea Technology, Dresden, Germany. Amarea Technology is a spin-off of Fraunhofer IKTS, the largest ceramics applied research institute in Europe, and has developed an Additive Manufacturing process that is able to use up to six different materials in a single build.

This Multi Material Jetting (MMJ) process is hoped to unlock new multi-dimensional combinations of various ceramics, metals, polymers and composites in both individual parts and functionally graded components.

Inspired by Low Pressure Injection Moulding, the high-filled thermoplastic base material developed and supplied by Amarea Technology is dispensed drop by drop. Due to the nanolitre volume, the drops solidify in a fraction of a second, considerably speeding up the entire build process. Thanks to the selective droplet-based AM technology, parts are said to achieve a considerably higher level of accuracy, density and surface quality than parts produced with Material Extrusion (MEX) processes, for example. This allows a material change to take place every 200 µm so that highly-functionalised components can be additively manufactured.

Beyond that, it is also possible to exactly define requested porosities at any selected position within the component. More than twenty-five different materials have already been introduced to the MMJ production technique, with the portfolio continuously growing, while important parameters, such as filling levels, porosity, gradient, layer height and density, can be freely and specifically defined.

Dr Johannes Homa, Lithoz CEO, stated, 'With our proud acquisition of a strategic share in Amarea Technology, we can't wait to see how our ultra-precise Lithoz LCM technology and Amarea Technology's MMJ system pointing on maximum material diversity will work hand-in-hand to unlock previously unachievable potentials. This will create the next generation of multi-material 3D printed applications from the semiconductor to aerospace industry – as first inquiries have already proven."

Steven Weingarten, Amarea Technology CEO, added, "The partnership with Lithoz and their belief in our technology inspire us. Lithoz's global reputation and its successful path to becoming the market leader in ceramic 3D printing are a model for the mission we are now taking in the field of multi-material 3D printing. We would like to express our gratitude to Johannes Homa and Johannes Benedikt for their trust and look forward to the exciting journey together."

www.lithoz.com
www.amarea.de

United States Metal Powders appoints Eric Degenfelder president

United States Metal Powders, Inc (USMP), Palmerton, Pennsylvania, USA, has announced the appointment of Eric Degenfelder as its president, effective February 2024. USMP, founded in 1918, is a global leader in the production of aluminium powder with two production facilities: AMPAL, Inc, also in Palmerton, and Poudres Hermillon, SARL (PH), in Hermillon, France. AMPAL has been operating in Palmerton for the last forty-two years, growing to be the largest US producer of aluminium powder. The company's products are sold globally and used in a wide variety of end markets including aerospace & defence, automotive, industrial, consumer, building & construction and energy.

"We are very excited to have Eric join our team and welcome him to USMP," said Louise Ramsey Thomas, board member and retiring president. "Eric brings a wealth of leadership experience in the specialty materials arena, and a strong track record of enhancing growth through innovation, customer centricity and production excellence. We have great confidence in the USMP leadership team now in place and our ability to continue to deliver in a differentiated way for our customers. Over the last year, this team has also been enhanced with the additions of Danny Perez as General Manager of AMPAL, and Jean-René Cavaille as General Manager of PH."

Degenfelder shared, "I am excited to join USMP and lead us into the next phase of growth. I have been highly impressed by the rest of the leadership team at AMPAL and PH, and was attracted to USMP's strong market position, customer centric philosophy and the orientation toward continued investment and growth enabled by its fortress balance sheet and low financial risk profile. Rest assured we will continue our strong heritage of customer focus and quality in the years ahead."

Degenfelder has leadership and cross-functional experience in specialty materials. He was CEO of U-C Coatings, headquartered in Buffalo, New York, for the past four years, and prior to that held a series of functional and geographic roles of increasing responsibility spanning product management, sales, marketing and strategy for Axalta Coating Systems, DuPont, Air Products and Millennium Chemicals. He received his BS in chemical engineering from Cornell University, and an MBA from Kellogg School of Management.

www.usmetalpowders.com

Eric Degenfelder has been named United States Metal Powders President (Courtesy Eric Degenfelder/LinkedIn)

Jiangsu Vilory Advanced Materials Technology raises $50M for facility expansion

Jiangsu Vilory Advanced Materials Technology Co., Ltd (VMP), located in Jiangsu, China, has successfully raised $50 million in two rounds of financing. The funding will be used to finance the construction of VMP's new production facility.

VMP offers a wide range of metal powders, produced using the company's vacuum inert gas atomisation (VIGA) powder production technology. Currently, the company operates ten VIGA machines and has an annual capacity of 750 tonnes.

It was stated that Phase II of the new facility is nearing completion and will soon be operational. Phase III of the development has now commenced.

The funding rounds were led by China State-owned Enterprise Mixed Ownership Reform Fund Co., Ltd., which became VMP's second-largest strategic external shareholder. This was followed by Jiangsu State-owned Enterprise Mixed Ownership Reform Fund (Limited Partnership) and other Chinese institutions.

China's Enterprise Mixed Ownership Reform Fund focuses on core technologies in key areas, striving to build a model for the reforming of state-owned science and technology enterprises and pioneering independent innovation. Its investment in VMP is expected to further strengthen the company's position in the industry, and promote the development of metals for the Additive Manufacturing sector.

Jiangsu Mixed Reform added that its investment is intended to help VMP strengthen its research and development capabilities, expand production capacity and serve the country's manufacturing strategy.

During 2023, VMP undertook two national key R&D projects and reported new breakthroughs in the research and development of five materials. The company also developed what is reputed to be the country's first single-furnace VIGA equipment with a charging capacity of 500 kg, which has now been put into production. Throughout the year, twenty-six invention patents were authorised, resulting in a total of 143 patents now authorised.

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D3-AM reveals its ceramic Micro Particle Jetting technology and LABII Additive Manufacturing machine

D3-AM GmbH, a subsidiary of the Durst Group based in Brixen, Italy, unveiled its Micro Particle Jetting technology and LABII Additive Manufacturing machine at this year's Formnext. Developed for high-performance ceramics manufacturing, D3's LABII is reported to allow the direct printing of water-based, highly-concentrated suspensions with almost any particle size and distribution. Once formed, the green parts undergo a sintering stage to produce the final component.

Stefan Waldner, Chief Product Officer at D3-AM, stated, "Material Jetting, from a theoretical standpoint, represents the most promising technology in Additive Manufacturing as it enables the construction of objects drop by drop, voxel by voxel. By overcoming material compatibility restrictions, our MPJ technology paves the way for the production of previously deemed impossible components."

D3 reported much interest in its technology at Formnext, leading to the initiation of a number of projects. These included the development of new materials and the exploration of potential applications. Thick-walled components and those made from Sintered Silicon Carbide (SSiC) were said to have drawn significant attention.

Christoph Gamper, CEO and co-owner of Durst Group, added, "With our presence at Formnext with the D3 LABII system, we are starting a new chapter at Durst: Material Jetting. The tradeshow has clearly shown that we are onwards in the premier class of materials – ceramics – and we look forward to scaling the printing systems, processes, and materials to open up a world of possibilities."

www.d3-am.com ■

D3-AM's Micro Particle Jetting technology has been developed for high-performance ceramics manufacturing, such as this heat exchanger (Courtesy D3-AM GmbH)

Wittmann Group expands Southeast Asia presence with Vietnam subsidiary

The Wittmann Group, headquartered in Kottingbrunn, Austria, has established a sales and service subsidiary in Ho Chi Minh City, Vietnam, with the aim of strengthening its presence in Southeast Asia. The new subsidiary is located near the international airport in the Tan Binh District of Ho Chi Minh City.

"Vietnam is growing rapidly more and more significant as a production location for the injection moulding industry," emphasised Michael Wittmann, owner and CEO of the Wittmann Group. "We are now responding to this trend by establishing Wittmann Vietnam Co. Ltd, in Ho Chi Minh City. This will enable us to serve our local customers there even more effectively and to provide flexible support for the development of new production facilities. With this action, we are further strengthening our customer base in Southeast Asia."

Wittmann has been present in Vietnam since 2015 through a local agency, and stated that it will continue working with Tao Bangkok (Vietnam) Co. Ltd to ensure optimal continuity and security for its customers in the region.

Giang An Le has recently been appointed as the General Manager of the company's new subsidiary. In his new role, he will be responsible for expanding the company's sales and service network in Vietnam. Giang is a graduate electrical engineer and brings with him twenty years of experience working in international production and mechanical engineering companies, with a focus on the plastics industry.

"The requirements for higher efficiency and quality standards are continually rising in Southeast Asia," said Wittmann. "Accordingly, innovative processing technologies, automation solutions and application technology counselling are in high demand."

www.wittmann-group.com ■

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Oechsler Group centralises production and management

The Oechsler Group, headquartered in Ansbach, Germany, is reorganising into three business units under the internally-named BE:FOCUSED programme. Oechsler is aiming to streamline structures, simplify the organisation, and plans to centralise operations. It was stated that evolving demands in tasks and job roles will result in the creation of new positions as well as job reductions. Globally, approximately 220 positions are impacted by the job cuts, with around 135 in Germany.

The three business units are built around Mobility, Innovative Solutions, and Health. Oechsler will close its Sporting Goods business, but will engage in sales in China if favourable opportunities arise. China will serve as a supplier base for multinational clients in the region. Changes are also expected in the Additive Manufacturing business, although not specified.

Oechsler stated that it will centralise worldwide production and its management in one location. The plants within the global group will focus on enhancing production efficiency. Sales responsibilities for regions and countries where Oechsler operates will be coordinated centrally in Ansbach, rather than being managed locally at the plants. The company's three German locations will reportedly continue to play a significant role.

"With BE:FOCUSED, we are launching an extensive investment programme for our successful future. Over the past few months, we have analysed very intensively how we can return to a profitable growth path in the long term. We too have been navigating increasingly stormy waters for several years due to changing market conditions, geopolitical changes and increased competitive pressure from our customers. For this reason, we will reorganise ourselves and set the right course again with BE:FOCUSED," stated Karl Ostler, CEO of Oechsler AG.

"We understand that ultimately, it's about people and not just 'jobs.' Therefore, we will proceed with caution," added Ostler. "Unfortunately, some colleagues will have to leave the company. We shared our plans with the General Works Council early on and in a transparent manner. I want to express my gratitude to our works council members for their positive discussions. They have passionately represented our employees' interests and acknowledged the necessity for action. This has allowed us to achieve an agreement and promptly provide clarity for our colleagues."

www.oechsler.com

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KBM Advanced Materials to distribute Sandvik Osprey metal powders in USA

Metal powder producer Sandvik AB, headquartered in Stockholm, Sweden, has announced that KBM Advanced Materials, LLC, based in Fairfield, Ohio, USA, will distribute its range of metal powders across the USA.

KBM, established in 2021, provides a supply network in the United States that helps bridge the gap between a dispersed customer base and metal powder producers. The collaboration will increase the availability of Sandvik's Osprey metal powders in the region.

"We are thrilled to offer our customers in the United States easy access to our market-leading range of Osprey metal powders," stated Andrew Coleman, Head of metal powder and Additive Manufacturing at Sandvik. "We are seeing increasing demand for our high-quality powders and have listened to our customers' needs for a US-based stock with short delivery times. We are very proud to offer a customer-centric business solution that will enable them to access high-quality alloys fast, without compromising on quality."

In April 2023, Sandvik announced the launch of its e-commerce platform, Osprey Online, designed to offer the European market a range of metal AM powders directly from stock. The partnership with KBM is expected to bring the same quick access to its Osprey metal powders in the US.

Luke Harris, Sales Director for metal powder business at Sandvik, added, "We often say 'The Right Partner is Everything', and that is certainly as true for us as it is for our end users. KBM shares Sandvik's focus on creating value for our customers and we feel very optimistic having entered this partnership to provide the US market premium metal powders quickly and efficiently. Our wide range of Osprey metal powders is well-known and trusted across several demanding industries, thanks to our long-standing experience, unique level of traceability, and overall quality. I'm convinced our metal powder offering in combination with KBM's attractive platform will prove beneficial to our US customers."

KBM offers a wide range of ready-to-order metal powders to customers in the metal AM and Metal Injection Moulding sectors through its online shop system.

www.kbmadvanced.com
www.metalpowder.sandvik

Personalised titanium smart watch housings developed by Incus and Element22

Sintered titanium smart watch housing before surface modification (Courtesy Incus/Element22)

Gerald Mitteramskogler, CEO of Incus GmbH, Vienna, Austria, has highlighted the potential of lithography-based metal manufacturing (LMM) technology, defined as a vat photopolymerisation process (VPP) by ISO/ASTM, in a detailed look at the production of personalised titanium smart watch housings. Working with Element22 GmbH, based in Kiel, Germany, the partners recognised the challenges of processing Ti64 in binder- or sinter-based Additive Manufacturing processes.

The R&D project resulted in a feedstock consisting of Ti64 powder at 55Vol% solids loading. The binder undergoes photopolymerisation during light irradiation, which results in the formation of a green part layer-by-layer. The green strength of the parts produced using LMM technology is said to be typically around 13 MPa in a three-point-bending setup, which is higher than other sinter-based AM processes. This high green strength allows for automated handling during extraction or de-powdering, and also facilitates the placement of the green parts onto the sintering setter, explained Mitteramskogler.

During the debinding and sintering process, the binder is thermally decomposed, leaving only the metal powder behind. A solids loading of 50Vol%+ is typically required to achieve dense and mechanically-functional parts, which can be sintered to produce final solid materials with theoretical densities exceeding 99%. The LMM process results in a surface finish as low as 2µm Ra (as-sintered) and a resolution of 35 µm.

In addition to developing a low-carbon photopolymer-based binder system, an adapted thermal processing route for Ti64 was also achieved. The resulting Ti64 is said to showcase 'remarkable' mechanical properties, exceeding ASTM F2885-17 standards for medical implant applications.

Beyond the advantages of mass customisation, LMM is said to result in MIM-like quality parts within hours, rather than weeks. Matthias Scharvogel, CEO of Element22, added, "Being a user of LMM, we can achieve significant savings in time to market for our customers, especially for high-quality prototypes and mass customisation."

Incus' HammerPro40 AM machine can reportedly build up to sixteen watch cases in less than 2.5 hours, with an annual production capacity of approximately 35,000 pieces. Once sintered, the watch housing undergoes a sandblasting stage before being coloured.

"With a fully-customised smartwatch housing, we can achieve a competitive cost structure compared to traditional manufacturing technologies, especially when designs can no longer be realised with MIM or CNC," Mitteramskogler concluded.

www.incus3d.com
www.element22.de

The watch housings undergo a sandblasting stage before being coloured (Courtesy Incus/Element22)

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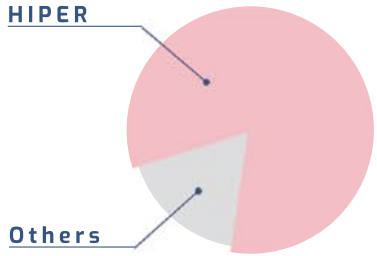
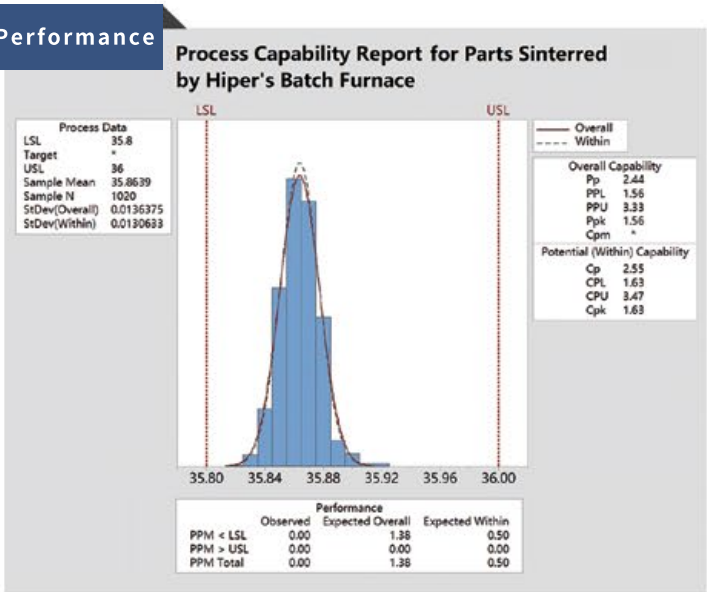


Performance



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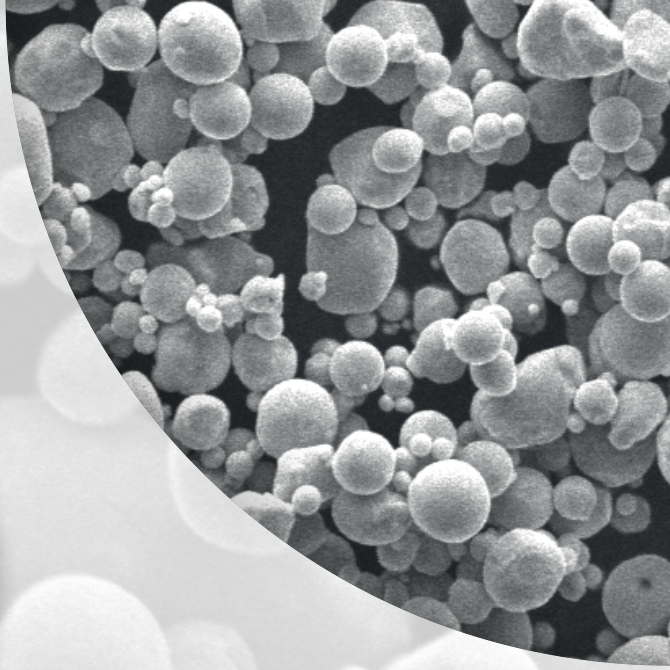

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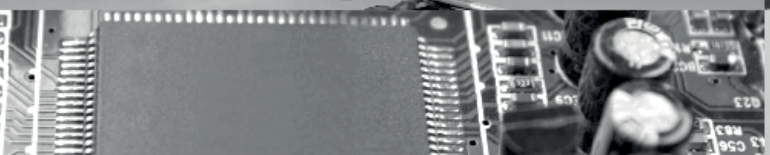

Markforged reports economic uncertainty leading to restructuring and workforce reduction

Markforged, headquartered in Watertown, Massachusetts, USA, has announced its financial results for the third quarter and nine months ended September 30, 2023. For Q3, the company reported revenue of $20.1 million, down from $25.2 million year on year. In the first nine months of 2023 its revenue was $69.6 million, down from $71.3 million in the first nine months of the previous year.

Markforged stated that a stronger than expected macroeconomic downturn had impacted demand for its Digital Forge and delayed orders toward the end of the quarter, with these challenges continuing into the fourth quarter. The persistent high cost of capital and uncertainty in the macro environment was reported to be restricting capital investment in the short term more than previously anticipated.

In response to these continuing economic headwinds, Markforged announced it has completed a restructuring that, coupled with other cost reduction efforts, is expected to deliver operating costs savings of approximately $9-12 million in 2024. The company added that most of these savings are being driven by a reduction in its workforce of approximately 10%.

"While the medium-to-long-term opportunity for Markforged to help manufacturers reduce costs and strengthen supply chain resiliency remains intact, our third quarter results reflect worsening macroeconomic headwinds in the final weeks of the quarter, which delayed several large deals that we had expected to close," stated Shai Terem, president and CEO of Markforged.

"We remain laser focused on profitability. In light of these headwinds, which have persisted into the fourth quarter, we have implemented cost reduction efforts to align our operating expenses to match anticipated near-term demand. With that, the overwhelming excitement surrounding our new product introductions at Formnext 2023 is a testament to the transformative impact our offerings are set to make in the manufacturing industry. In particular, the customer enthusiasm surrounding the FX10 is reinforcing our confidence that Markforged is well-positioned for strong growth as macroeconomic uncertainty clears," added Terem.

For Q3 2023, gross margin was 45.7% compared to 48.6% in Q3 2022. Operating expenses were $59.6 million, inclusive of a non-cash goodwill impairment charge of $29.5 million as a result of the company's performance during Q3 and decline in forecasted revenue, compared to $35.1 million. Net loss was $51.4 million compared to the $23.0 million in Q3 2022.

www.markforged.com

Retech's new integrated plasma gas atomiser aims for cheaper titanium powders

Retech, a division of the Seco/Warwick Group based in Swiebodzin, Poland, and with facilities in New York and California, USA, has announced the development of an integrated plasma gas atomiser (PGA) that is claimed to achieve atomisation rates greater than ten-times the rate of currently available technologies.

Retech's integrated system utilises its Plasma Arc Melting (PAM) technology, in combination with gas atomisation, to process a wide variety of refractory and reactive alloys, amorphous metals, or superalloys. The atomiser can use most feedstock formats – including sponge, compacts, recycled scraps and ingots – and enables continuous processing via an airlock feeder system that doesn't interrupt melting to recharge. The atomiser also eliminates nozzles, which can be prone to clogs, thus improving reliability and simplifying cleaning and product changeover.

"At Retech, we are too busy commissioning new furnaces, and trusted by customers with too many trade secrets and defence clearances, to be able to boast of our accomplishments much, so it is a delight to have a new innovation in PGA that we can shout from the rooftops!" stated Earl Good, Retech's Managing Director and President.

While the company's suite of melting technologies is capable of melting a wide range of reactive and refractory elemental metals and alloys, the economical production of titanium powder, in particular, offers great potential. Retech is seeing growing interest in titanium use, with companies finding ever more applications for the metal.

To support the growth of Retech's PGA technology, parent company Seco/Warwick Group recently secured a $10 million subsidised loan in order to allow the company to expand PGA equipment manufacturing capabilities.

"This dovetails perfectly with our recent membership in America Makes, the National Additive Manufacturing Innovation Institute," added Good. "Sure, I look forward to what the big players will do with the less expensive powder metals Retech will enable, but they already have access to the material and technology, but what really excites me is the opportunity to see what creative young minds can do with this once Retech makes it accessible enough that they can afford to have fun with Ti AM in a garage-tech sense. Take bold steps without fear of mistakes. It is not so much about making the existing tech less costly, the excitement is in the fields where titanium will become a feasible option, where it was not before."

www.secowarwick.com
www.retechsystemsllc.com

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Jalin Ketter appointed as CEO of PVA TePla

PVA TePla AG, headquartered in Wettenberg, Germany, has announced that Jalin Ketter was appointed CEO of the company on January 1, 2024. Ketter, who has been PVA TePla's Chief Financial Officer since June 2020, was named Spokesperson of the Management Board in July 2023. It was stated that she will fulfil the CEO position in addition to her duties as CFO.

"My goals are clear: together with our excellent team, I will drive PVA TePla's profitable growth and further expand our market position as a leading technology company in the fields of material solutions and metrology," Ketter stated.

Ketter has been a member of PVA TePla's management board since 2015.

"The decision to appoint Jalin Ketter as CEO not only recognises her impressive expertise and leadership skills, but also her many years of valuable work for PVA TePla," explained Alexander von Witzleben, Chairman of the Supervisory Board of PVA TePla. "She has made a significant contribution to our success in recent years. We are convinced that she will lead our organisation into the future with foresight and determination. This step underlines our confidence in Jalin Ketter, the management team and our shared vision."

Since Ketter's appointment as Spokesperson of the Management Board, she has led PVA TePla alongside COO Oliver Höfer. It was added that the finance department has already been bolstered with the appointment of Elke Kleemann as the Head of Finance.

www.pvatepla.com

Jalin Ketter has been appointed CEO of PVA TePla beginning 2024 (Courtesy PVA TePla)

Gasbarre move to larger St Marys facility underway

Gasbarre has reported that the previously-announced relocation of its St Marys, Pennsylvania, USA, facility is now well underway. The move will take the company to a 14,000 m² facility - around triple the size of its current location.

Gasbarre anticipates the upgraded facilities and state-of-the-art equipment will streamline processes and enhance productivity for its growing customer base. The faster turnaround times and expanded services are also expected to position the company to better serve its local and international customers.

The move will treble the size of its existing St Marys, Pennsylvania, facilities (Courtesy Gasbarre)

Gasbarre manufactures a wide range of powder compaction presses, including mechanical, hydraulic, high-speed, isostatic, and electric press types. The company also has an extensive line of industrial thermal processing systems, including continuous atmosphere to batch atmosphere and continuous vacuum to batch vacuum furnaces. Additional product lines include precision tooling, industrial automation, and contract manufacturing.

"Our commitment to excellence and customer satisfaction remains unwavering, ensuring that our clients find the perfect machinery tailored to their specific manufacturing processes," Gasbarre posted in an update on the move. "As we transition to this larger space, we're excited about the possibilities it brings for innovation, growth, and continued success."

www.gasbarre.com

Mitchell Yang appointed Managing Director for Arburg in Taiwan

Arburg GmbH + Co KG, headquartered in Lossburg, Germany, has appointed Mitchell Yang as its Managing Director of its subsidiary in Taichung, Taiwan. Yang has taken over from Michael Huang, who successfully established the subsidiary in 2015 and has built a strong, competent local team.

Mitchell Yang is the new Managing Director of Arburg in Taiwan, succeeding Michael Huang (Courtesy Arburg)

Yang holds a Bachelor's degree in Electronic Engineering and an Executive MBA. He also brings extensive management and sales experience to his new job.

The Taiwanese market is seen as an important one for Arburg. As a leading centre for the production of electronic semiconductors, the country offers mechanical engineering and injection moulding experts a wide range of market opportunities. Industries such as 3C electronics (computers, consumer electronics and communication), sporting goods and medical technology are developing at a rapid pace locally. In addition, manufacturers in Taiwan are focusing heavily on automation and digital transformation.

These are all areas that Arburg serves. To fully support these customer needs, the subsidiary in Taichung has a showroom with two latest-generation Allrounders equipped with the new Flexlift linear robotic system for Asia. This enables Arburg Taiwan to offer extensive application-related advice. In the training area, customers can also benefit from detailed application-related support and complete training courses on all aspects of Arburg technology.

"Continuity is a key factor in motivating customers to remain loyal to a company," stated Yang. "This is also true for Taiwan – and is why they can count on Arburg to be their reliable partner in the Taiwanese market for years to come."

It was added that in the coming months, Yang will take part in an intensive induction programme in close cooperation with the Arburg headquarters in Lossburg, Germany. This will ensure that the high standard of all services in keeping with the Arburg brand phrase "Wir sind da." ("We are here for you.") will continue to be provided at the same level as in Germany.

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SINTX subsidiary and US Army partner to explore ceramic Additive Manufacturing and ceramic matrix composites

SINTX Technologies, Inc, a manufacturer and developer of advanced ceramic materials and related technologies based in Salt Lake City, Utah, USA, has announced that its wholly-owned subsidiary Technology Assessment & Transfer, Inc, (TA&T) has entered into a Cooperative Research and Development Agreement (CRADA) with the US Army Combat Capabilities Development Command Army Research Laboratory (DEVCOM ARL). This partnership is expected to leverage the strengths of both organisations in the areas of ceramic Additive Manufacturing and ceramic matrix composites (CMCs).

According to its website, the US Army DEVCOM Army Research Laboratory is the US Army's research laboratory strategically placed under the Army Futures Command. DEVCOM ARL is the Army's sole foundational research laboratory focused on cutting-edge scientific discovery, technological innovation, and transitioning capabilities for the future Army.

SINTX's Technology Assessment and Transfer, Inc, facility located in Millersville, Mayland, started its ceramic Additive Manufacturing operations in the mid-1990s, manufacturing its first component in 1998. SINTX now provides prototype and Low-Rate Initial Production (LRIP) ceramic AM services, sells ceramic-filled resins that customers use in their own manufacturing processes, and works with multiple customers in the development of AM solutions for new materials.

In parallel to ceramic Additive Manufacturing, SINTX's Maryland site has also been developing ultra-high temperature CMCs, and building extensive capabilities in the densification of fibre-based preforms using both chemical vapour infiltration and polymer infiltration and pyrolysis.

Ann Kutsch, General Manager of the Maryland site, commented, "We have a highly-skilled team of engineers and technicians here in Maryland, all of whom are instrumental in pushing this cutting-edge work forward. I look forward to optimising our offerings in these markets while also working with DEVCOM ARL to build both teams' knowledge and capabilities in advanced technologies."

www.sintx.com
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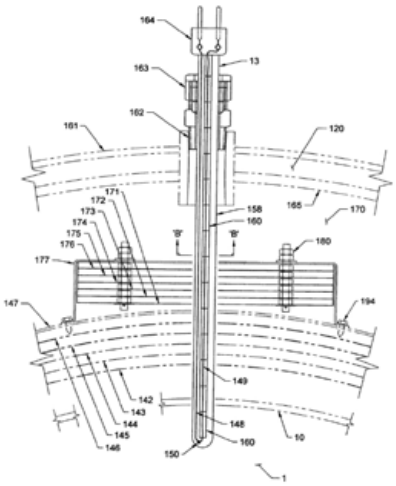
Solar Manufacturing receives US patent for vacuum furnace control thermocouple

Solar Manufacturing, Inc, located in Sellersville, Pennsylvania, USA, has been granted a patent for an enhanced vacuum furnace control thermocouple design. This new design is said to be particularly beneficial for controlling operating temperatures ranging from ambient up to 649°C (1,200°F), especially within smaller diameter hot zones of 91.5 cm (36") or less.

Typically, the outer ceramic protection tube of the conventional control thermocouple design serves as a heat sink. This thermal conduction, or heat loss, is compounded by the shorter length of the thermocouple assembly. As a result, the control thermocouple operates at a lower temperature, thereby increasing the power output to the furnace heating elements to maintain the set-point temperature. Consequently, the workload temperature becomes hotter than the furnace temperature. This phenomenon is more noticeable at lower processing temperatures (<649°C / 1,200°F).

The new thermocouple design from Solar Manufacturing aims to reduce unwanted thermal conduction losses in the assembly. This configuration has also shown improved temperature uniformity survey results. For compliance with AMS 2750 standard temperature uniformity specifications, proper positioning of control thermocouples in the hot zone is crucial to ensure accurate survey thermocouple measurements without the need for correction factors.



Solar Manufacturing has received a patent for a control thermocouple for vacuum heat treat furnaces (Courtesy Solar Manufacturing)

The patent inventor is William R Jones, owner of Solar Manufacturing.

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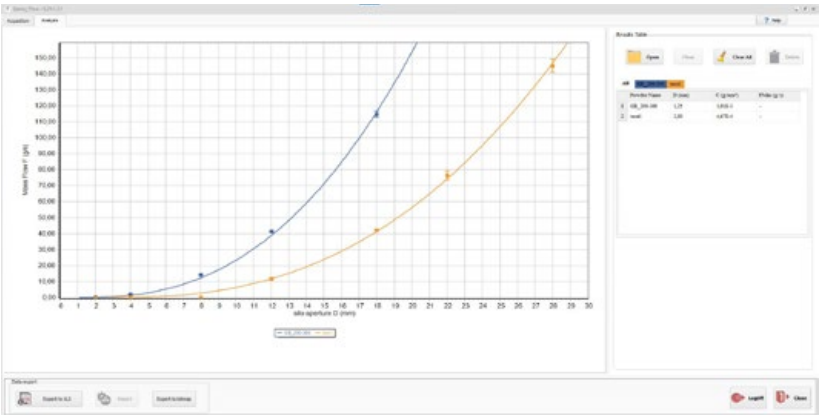
Granutools releases GranuFlow software update

Granutools, based in Awans, Belgium, has unveiled new software to pair with the GranuFlow powder and granular material flowmeter for enhanced powder analysis. The instrument fits the flowing curve to a theoretical model, and from this, it derives two critical indexes that encapsulate the unique interplay of flowability and cohesiveness of the powder. These indexes are then integrated into a comprehensive diagram, providing a holistic view of the powder's characteristics.

Granutool's new software takes users through each step via a streamlined interface, enabling precise measurements and reproducible results.

GranuFlow's latest software update includes the following new features:



The software will pair with the GranuFlow powder and granular material flowmeter for enhanced powder analysis (Courtesy Granutools)

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- Automatic connection to the GranuFlow instrument

www.granutools.com

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Ceramaret adds XJet ceramic Additive Manufacturing machine

XJet, based in Rehovot, Israel, has announced that Ceramaret, a Swiss technical ceramic manufacturer, has acquired an XJet Carmel 1400C Additive Manufacturing machine. The decision followed an intensive benchmarking process, that concluded XJet's NanoParticle Jetting process could produce parts that the team had previously considered impossible.

"XJet technology will provide us with new capabilities, new geometries we can offer our customers, whilst also delivering exceptional time-to-market. Taking seventy-two hours from a new file to a finished part, it's an extremely fast process," stated Senad Hasanovic, Ceramaret VP of Innovation. "However, it was the quality and global cost-per-part that really impressed me, demonstrating that this was an industrially competitive solution. We couldn't ignore XJet's remarkable capabilities after that process, the applications XJet will open up for Ceramaret are remarkable. We saw parts that are beyond the reach of any other production method. In particular, there were parts with internal shapes or channels down to 300 microns in diameter and near 300 mm long, which either cannot be produced in a single piece or cannot be produced in bulk with our existing techniques."

Since then, Ceramerat has worked with XJet to test around thirty different products, consisting of around 300-400 parts. The team also visited XJet's AM Center in Rehovot, observing the entire production process.

Hasanovic added, "We scrutinised each of the test parts, polishing them and checking their structural integrity, their porosity, functionality and more. These investigations convinced us that the parts would meet the needs of our customers and add value to the manufacturing services we offer."

Andy Middleton, XJet Vice President Europe, commented, "Ceramaret is known across numerous industries for its expertise in every aspect of ceramic production, so their decision to embrace XJet's technology underscores its quality and value. Achieving near-net shape is a proficiency Ceramaret particularly prides itself on – as does XJet. Our technology achieves it through a combination of unique capabilities, from NanoParticle Jetting to our post-processing steps, whether geometries are simple or complex."

XJet uses nano particles to achieve fine detail and precision. The creation of internal cavities or channels, usually a labour-intensive post-processing task (sometimes impossible with other technologies) is made easier with XJet's proprietary soluble support material that simply dissolves. Hasanovic described XJet post-processing as a "repeatable, stable, industrial-grade process that we feel already familiar with."

www.xjet3d.com
www.ceramaret.com

Metal Powder Products LLC names Jon Jensen as its new CEO

Metal Powder Products LLC (MPP), a manufacturer of Powder Metallurgy and Metal Injection Moulding parts, has announced the appointment of Jon Jensen as its Chief Executive Officer. MPP is a portfolio company of Mill Point Capital and is based in Noblesville, Indiana, USA.

Jensen brings more than thirty years of global manufacturing experience to MPP. Prior to joining MPP, he served as president and CEO of NAI, leading the business through an operational and financial transformation. His extensive background includes several key executive roles at L-com Global Connectivity, Group Dekko, Alcoa, ITT, and Eaton, where he had a strong track record of mobilising and collaborating with his teams to achieve key objectives rapidly.

"We are excited to welcome Jon to the MPP team as we navigate the next chapter of our growth journey. He is an accomplished CEO with a proven track record of driving strong financial results, instilling financial and operational discipline, and demonstrating inspirational leadership," stated Antony Besso, Executive Chairman.

Jensen holds a Bachelor of Science degree in Mechanical Engineering Technology from Lake Superior State University. His educational background, leadership experience, and understanding of diverse industrial sectors are said to make him ideally suited to lead MPP.

www.MPPinnovation.com

Jon Jensen has been named CEO of Metal Powder Products (Courtesy Metal Powder Products)

Tritone Dim brings metal and ceramic Additive Manufacturing to Impact Labs

Impact Labs, an AM service provider based in Tel Aviv, Israel, has added a Tritone Dim metal AM machine from Tritone Technologies. The metal and ceramic AM technology will expand the range of materials offered to Impact Labs' customers.

"Impact Labs has a vision to enable our customers to bypass the high barriers of owning an industrial AM machine and allow R&D and manufacturing access to the knowledge and operations of our printers and infrastructure," stated Idan Keisar, co-founder of Impact Labs. "We are a meeting place for humans and machines in order to quickly solve challenges, so adding a new technology that enables us to switch between metal materials twice a day helps us boost innovation that creates new AM applications, which is the actual frontier for AM market today."

Tritone Dim machine installed at Impact Labs facilities (Courtesy Tritone Technologies)

"Tritone's innovative technology successfully tackles critical challenges within the Metal AM sector," shared Ziv Sadeh, CEO, SU-PAD. "Allowing for Tritone's Dim system to manufacture metal and ceramic parts in Israel will provide companies in the industry the ability to offer complex features they couldn't offer in the past, thus allowing them to reach potential customers they couldn't reach before."

Tritone's Dim AM process is based on the company's MoldJet technology, a powder-free, sinter-based Additive Manufacturing process said to enable the industrial production of high-quality metal and ceramic parts at an industrial speed. Designed for producing a large quantity of high-density parts with complex geometries, MoldJet allows a simple changeover between a variety of metals and ceramics for parallel manufacturing of parts of various sizes, shapes, and applications.

"Impact Labs and Tritone share a common objective - to elevate the manufacturers' capabilities by introducing a cutting-edge AM technology," said Ohad Dolev, Director of Business Dev. & Application, Tritone Technologies.

www.tritoneam.com
www.impactlabs.tech
www.su-pad.co.il

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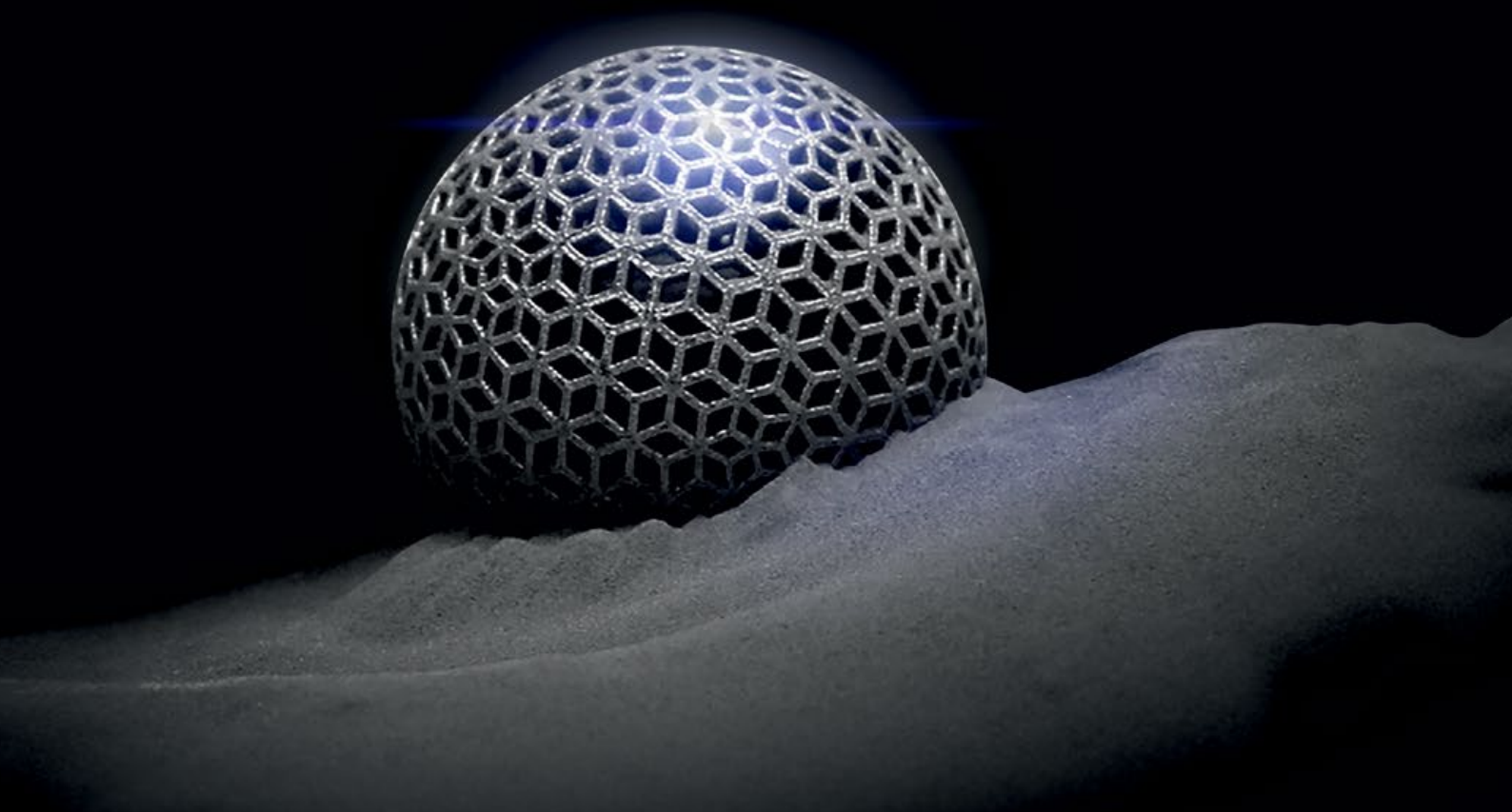

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Thomas F Murphy to receive Lifetime Achievement Award at PowderMet2024

Thomas F Murphy, FAPMI, Senior Scientist, Research and Development, at Hoeganaes Corporation in Cinnaminson, New Jersey, USA, has been chosen to receive the Kempton H Roll Powder Metallurgy Lifetime Achievement Award by the Metal Powder Industries Federation (MPIF). The award, named after the founding executive director of the MPIF, acknowledges the exceptional accomplishments and achievements of individuals who have dedicated their careers and lives to the field of PM and related technologies.

Murphy is only the fifth person to be presented with the award since its inception in 2007.

The award ceremony will take place during the opening session of PowderMet2024 International Conference on Powder Metallurgy & Particulate Materials and AMPM2024 Additive Manufacturing with Powder Metallurgy events, held in Pittsburgh, Pennsylvania, USA, June 16–19, 2024.

Murphy is a renowned expert in the field of ferrous PM microscopy. He has played a crucial role in developing sample preparation, characterisation methods and testing for metal powders and PM components. He continues to educate the industry about the impact of microstructure on the entire PM process. Recently, his research has expanded to include the effects of microstructure on the Additive Manufacturing process.

Murphy organised and coordinated the APMI International (APMI) PM Metallography Competition from 1989 to 2008. He also oversaw the Excellence in Metallography Awards from 2009 onwards. Additionally, he has served on the Board of Directors for the International Metallographic Society (IMS) and has been actively involved as a judge for the IMS Metallography Contest. In recognition of his contributions, Murphy received the MPIF Distinguished Service to Powder Metallurgy Award in 2005 and the APMI Fellow Award in 2007.

Murphy has been an enthusiastic MPIF Technical Conference Program Committee member since 1990. He co-chaired PowderMet2007, assisted with the development of the online Guide to PM Microstructures, and has been a longtime instructor at several MPIF seminars and courses.

Thomas F Murphy will receive his Kempton H Roll Powder Metallurgy Lifetime Achievement Award at PowderMet2024 (Courtesy MPIF)

Additionally, he is a member of the APMI *International Journal of Powder Metallurgy* Editorial Review Committee.

Murphy has authored or co-authored more than seventy-five technical publications, four of which were recognised as Outstanding Technical Papers by MPIF. Many of these publications serve as guidebooks for proper sample preparation, etching, and analysis techniques. From 1983 to 1990, he also served as an adjunct faculty member at Drexel University Evening College.

www.mpif.org

Tekna's $20 million government funding plan extended

Tekna Holding ASA, Sherbrooke, Quebec, Canada, has announced the extension of a CA $20 million contribution agreement with the Canadian federal government's Strategic Innovation Fund (SIF) programme. Under the terms of the reported amendment, the maximum amount to be disbursed remains unchanged at CA $20 million, however the programme has now been extended to March, 2027. To date, CA $6.6 million has been disbursed.

"This amendment is a significant milestone, confirming Tekna's position as an industry leader," stated Luc Dionne, CEO of Tekna. "The extended support and enhanced financial framework under the SIF programme are instrumental in driving forward our strategic initiatives. We are committed to leveraging this opportunity to further our technological advancements and market leadership."

The SIF programme aims to stimulate high-quality business investments across various sectors. It supports R&D initiatives that enhance technology transfer, commercialisation of innovative products, services, and processes, and encourages the growth of innovative firms.

"The SIF's contribution has been pivotal in our growth journey," added Espen Schie, CFO of Tekna. "The amended terms not only provide us with financial flexibility but also affirm the value of our ongoing projects. We are grateful for the support of Innovation, Science, and Economic Development Canada (ISED) throughout the amendment process. This collaboration is a testament to our commitment to innovation and sustainable development in the advanced materials sector."

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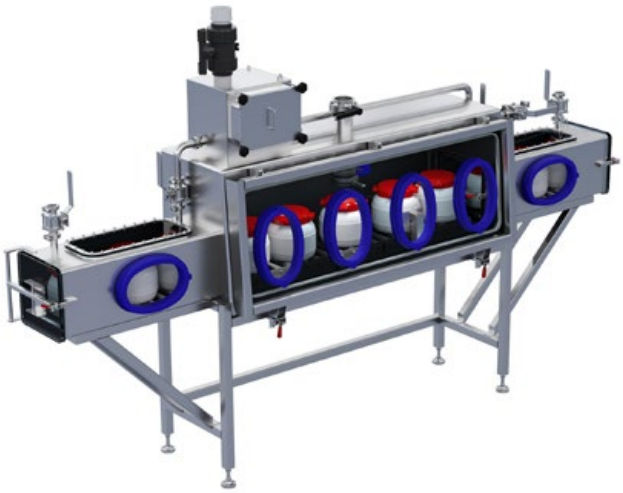
Custom Powder Systems introduces new metal powder packaging solution

Custom Powder Systems, Springfield, Missouri, USA, has introduced the Metal Powder Packaging System, designed to address the specific challenges of dispensing and packaging large quantities of metal powders. With its advanced features, it aims to improve packing efficiency in the Additive Manufacturing industry.

Problems in traditional dispensing processes are intended to be solved by transitioning from bulk manufacturing lines to a manual dispensing step. This step involves weighing precise quantities into smaller containers for shipping. The system utilises a manual conveyor and an integrated scale with a digital readout under the discharge tubes, enabling high measurement accuracy.



Custom Powder Systems has introduced the Metal Powder Packaging System, its latest innovation in powder handling (Courtesy Custom Powder Systems)

The design prioritises safety by incorporating a vacuum exhaust filtering system to maintain a clean and controlled environment during the packaging process. A lift-up gull wing door design provides easy access. Moreover, in-and out-feed airlocks actively prevent cross-contamination, whilst a manually-controlled inert environment helps to preserve product quality.

The primary application of the Metal Powder Packaging System is at the end of manufacturing processes. Here, atomised products are mixed, screened, and dispensed into containers for distribution. This design is intended to significantly benefit high-purity powders used in industries like aerospace and medical fields.

This system is engineered for environments where contact with oxygen is restricted or undesirable. It safeguards the integrity of metal powders and includes optional features for automation and customisation based on specific industry needs. By mitigating the risks of oxidation, static discharge, and off-gassing, it enables powders to maintain their quality throughout the packaging process.

www.custom-powder.com

Ceramics Expo 2024 conference programme released

The conference programme for Ceramics Expo 2024, set to take place April 30–May 1, 2024, at the Suburban Collection Showplace, Novi, Michigan, USA, has now been released. The 2024 event will cover a range of areas, including innovation in ceramic materials, supply chain sustainability, piezoelectric ceramics, workforce and talent development, Additive Manufacturing, advanced ceramic innovations in aerospace and electronics, and next-generation solid-state batteries.

The programme includes the following sessions:

Day 1: Materials & product development

- Ceramics Driving Aerospace Innovation
- Surveying The Ceramics Supply Chain – From Reshoring To Sustainability
- Ceramics in Next-Generation Solid-State Batteries
- 3D Printing with Hydroxyapatite

Day 2: Innovation & manufacturing

- Solving the Workforce and Talent Development Crisis in Ceramics and Glass
- Innovation in Ceramic Materials for Microelectronics
- Manufacturing Advanced Ceramic Parts for Aerospace and Electronics
- Piezoelectric Ceramics – From Bulk to Thin Film and BTO

Confirmed speakers currently include: Mark Wolf, Kyocera; James Weigner, Lockheed Martin Fellow; Craig Rosenblum, Himed; Eric Bert, Exentis Americas; Shawn Allan, Lithoz America; Tony Finoli, McDanel Advanced Material Technologies; Amanda Engen, American Ceramic Society; John Ciraldo, and Alla Smirnova, Center Solid-State Electric Power Storage (CEPS).

Ceramics Expo 2024 is free to attend, but visitors must pre-register in advance.

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Oxford Instruments launches Innovation Centre for advanced material analysis

Oxford Instruments plc, a materials analysis solutions provider headquartered in Abingdon, Oxfordshire, UK, has established the Oxford Instruments Innovation Centre at the company's High Wycombe site. The centre is said to form part of the company's ongoing contribution to scientific advances, in line with its goal of enabling a greener, healthier, more connected, and advanced society.

To mark its inauguration, individuals from the scientific, research and local communities were invited to the new facility. After a welcome speech from Dr Ian Wilcock, the Managing Director of Oxford Instruments' Materials Analysis group, attendees were given demonstrations of the centre's material analysis technologies and a tour of its facility.

"Understanding the nature, structure and property of materials is fundamental to advancement in many fields of scientific research and product development, from renewable energy and advanced communications to healthcare and food science, and a wealth of areas in between," stated Dr Wilcock. "The centre allows us to showcase our world-leading analytical instrumentation and facilitate the provision of training by our technique experts. It is also intended as a hub for collaboration, where invited scientists and researchers can access both the technology and the expertise at the core of the Innovation Centre."

www.oxinst.com

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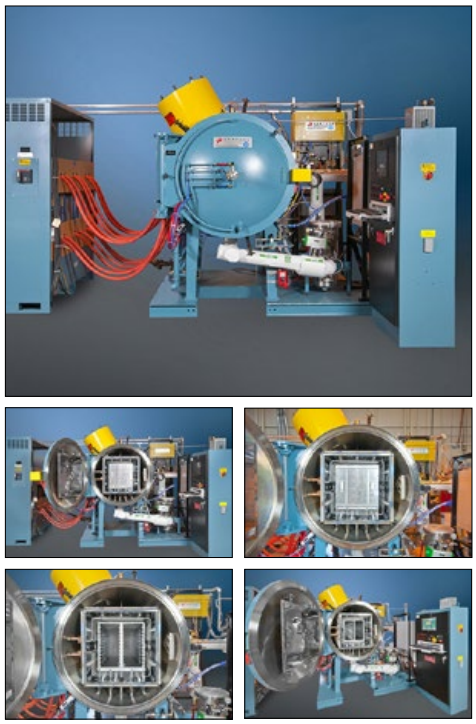

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CMG appoints Mark Leonard as Technical Sales Manager

CMG Technologies, based in Woodbridge, Suffolk, UK, has announced the appointment of Mark Leonard as the company's Technical Sales Manager. The new role has been created following Indo-MIM's acquisition of CMG, with growth stated as a key goal for the future.

In his new position, Leonard will be travelling across the UK to generate new clients and promote the work of both CMG and Indo-MIM. Additionally, he will continue to build on existing relationships with the company's client base.

Leonard began his career in the non-ferrous metals industry and brings more than twenty-five years of experience in the engineering and manufacturing sector. His diverse knowledge and practical experience are reported to have helped him understand the vast and complex work of CMG.

www.cmgtechnologies.co.uk

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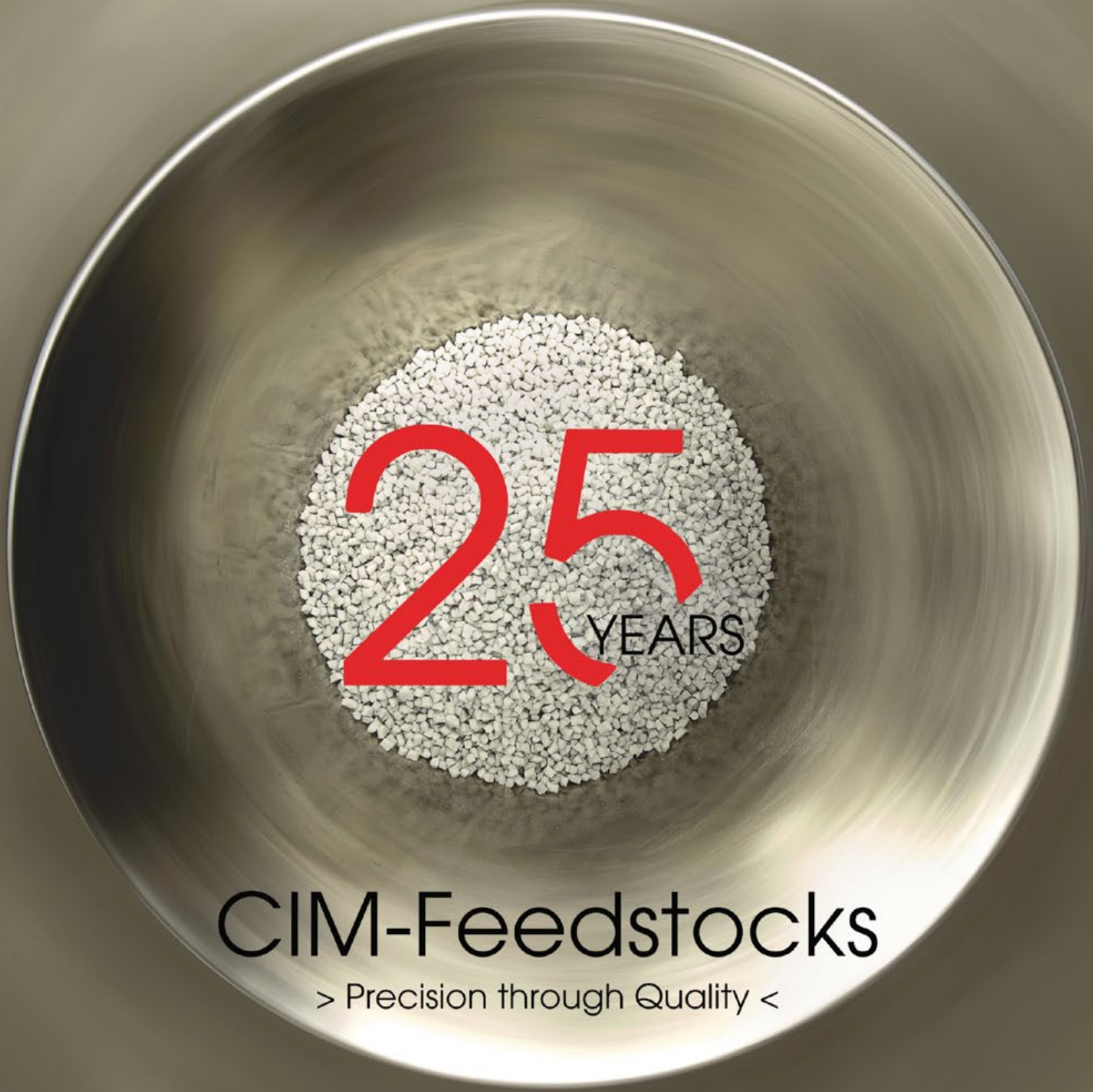

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Arburg Senior Partner Eugen Hehl passed away aged 94

Eugen Hehl, Senior Partner of Arburg GmbH + Co KG, Lossburg, Germany, passed away on December 12, 2023, at the age of ninety-four. Hehl was known for his contributions to the development of Arburg's global sales and infrastructure, as well as his strong social commitment.

As Chairman of the Management Team for many years and responsible for global sales at Arburg, Eugen Hehl significantly contributed to the company's global success. With a technical background and a strong sales instinct, he played a decisive role in shaping the family business for more than seven decades in co-operation with his brother Karl, who passed away in 2010.

Hehl's ideas and construction solutions gave the company a unique profile worldwide. As the Managing Partner and the 'master builder of the company,' he was instrumental in the global success of the family business.

In 1951, Eugen Hehl started to develop his own regional sales structures through extensive travel. By 1957, he elevated the company's sales to an international level by participating in the first trade fair in Amsterdam, Netherlands. Throughout his life, Hehl pursued his visions with commitment. As early as 1962, he travelled to Japan and the USA to further increase machine sales.

Hehl was instrumental in construction activities at the main plant and the gradually-established Arburg subsidiaries worldwide. With foresight, he partially demolished buildings in Lossburg in 1966 that were between two and four years old. This was to enable grid construction, which improved future expansion alternatives on the company premises. Many Arburg subsidiaries worldwide bear a resemblance to the headquarters in terms of exterior design, making them easily recognisable.

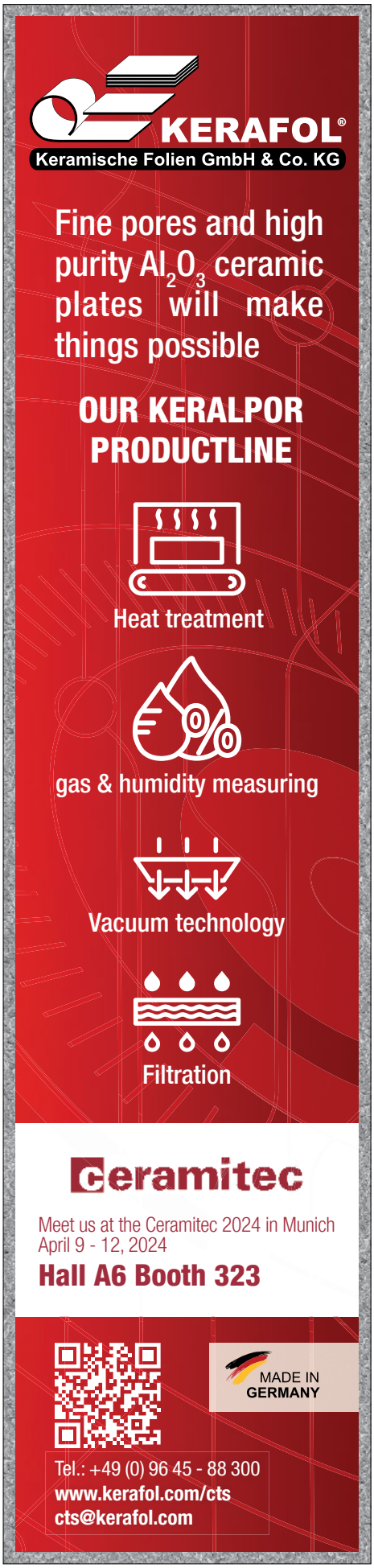
Eugen Hehl was highly-respected in his hometown of Lossburg, at Arburg, and far beyond the region, both personally and professionally. Along with his brother Karl, Eugen Hehl was recognised for his strong social commitment. They established the Gebrüder Hehl Foundation in Lossburg, which officially started its work in 1999. The foundation operates a retirement home through Bruderhaus-Diakonie, a non-profit Christian diaconal foundation in Baden-Württemberg. This home offers assisted living, short-term care, and elderly care. Eugen Hehl was also involved in church activities, including the choir of the Lossburg parish.

In November 2000, Eugen Hehl was awarded the Federal Cross of Merit by the Federal Republic of Germany for his accomplishments. In 1990, the company was awarded the Baden-Württemberg Business Medal, followed by the Baden-Württemberg Competence Award for Innovation and Quality in 2015. Other accolades include honorary citizenship of the municipality of Lossburg in November 1997, the Global Master Craftsman's Certificate in 2005, and the Business Management Award in 2007, presented by the American Society of Plastics Engineers (SPE) to Eugen and Karl Hehl for their joint life's work.

Eugen Hehl was also inducted into the 'Plastics Hall of Fame' in 2015. In 2020, he was awarded the Richard Vieweg Medal of Honour, the highest award of the Association of German Engineers (VDI).

The Managing Partners, in particular Juliane and Michael Hehl – Hehl's two children – along with their cousin Renate Keinath, who collectively represent the third generation of management, will remember him with honour and gratitude. This sentiment, it was stated, is shared by all the Managing Directors and employees.

www.arburg.com



Registration opens for EPMA's 2024 Powder Metallurgy Summer School

The 22nd Powder Metallurgy Summer School, organised by the European Powder Metallurgy Association (EPMA), will take place from July 15-19, 2024. The event will be hosted in partnership with the Politecnico di Torino – Sede di Alessandria in Alessandria, Italy. The programme is intended to provide an in-depth insight into the field of Powder Metallurgy.

The EPMA PM Summer Schools aim to provide advanced teaching on the advantages and limitations of PM to participants from across Europe. The programme is led by some of Europe's leading academic and industrial experts. The Summer Schools offer an opportunity for young scientists and engineers to interact with senior figures in the PM industry, allowing them to broaden their knowledge through direct technical discussions.

The application deadline is May 1, 2024.

www.epma.com

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Nabertherm highlights furnaces for Metal Injection Moulding

Nabertherm GmbH, headquartered in Lilienthal, Germany, has published a guide outlining the debinding and sintering stages in the Metal Injection Moulding process, along with the furnace technology it now offers to meet these needs.

Debinding of MIM parts

The debinding process can be carried out in several ways, explains Nabertherm. This can be either thermally in an inert atmosphere or under hydrogen in a vacuum, catalytically in a nitric acid-nitrogen atmosphere, or in a tank containing water or solvent. The furnace required for the thermal or catalytic debinding process is a gas-tight hot-wall retort furnace, and for this, Nabertherm offers a number of furnaces from its NR model series.

Safety technology plays a critical role in ensuring the safe operation of retort furnaces when dealing with organics and flammable process gases. Nabertherm's retort furnaces can effectively detect and respond to potential hazards, ensuring the protection of personnel, equipment, and the surrounding environment during the handling and processing of flammable substances during the debinding step.

The sintering stage

In the subsequent combined debinding and sintering process, which takes place in a protective gas or reactive gas atmosphere, or in a vacuum, the brown part is sintered into the finished part. Due to the high sintering temperatures, this process step is typically carried out in a cold-wall retort furnace. For this application, Nabertherm offers furnaces from its VHT model range.

A furnace can be tailored specifically to the material for this process step in various configurations. For sintering stainless steels under a hydrogen atmosphere, for example, furnaces with heaters and insulation made of molybdenum and heating elements made of tungsten, are used. Furnaces with graphite heaters and insulation made of graphite felt are excellent for low-alloy steels that can be sintered in a non-reducing process gas atmosphere.

An important part of the sintering furnace is an inner process box, continues Nabertherm. Due to the release of residual binders before the sintering process, an additional inner process box, through which the exhaust gas is directly vented to the exhaust stack, can significantly reduce contamination of the furnace chamber. For a graphite furnace, the insert box is made of graphite, while for a metallic-heated furnace, a box made of molybdenum (potentially tungsten-reinforced) is used.

The guide to Metal Injection Moulding, along with a others, can be downloaded from the website.

www.nabertherm.com

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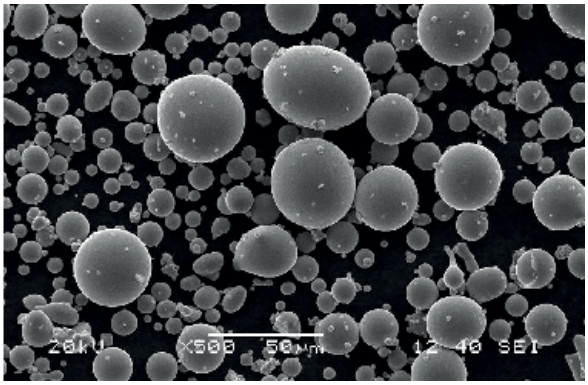

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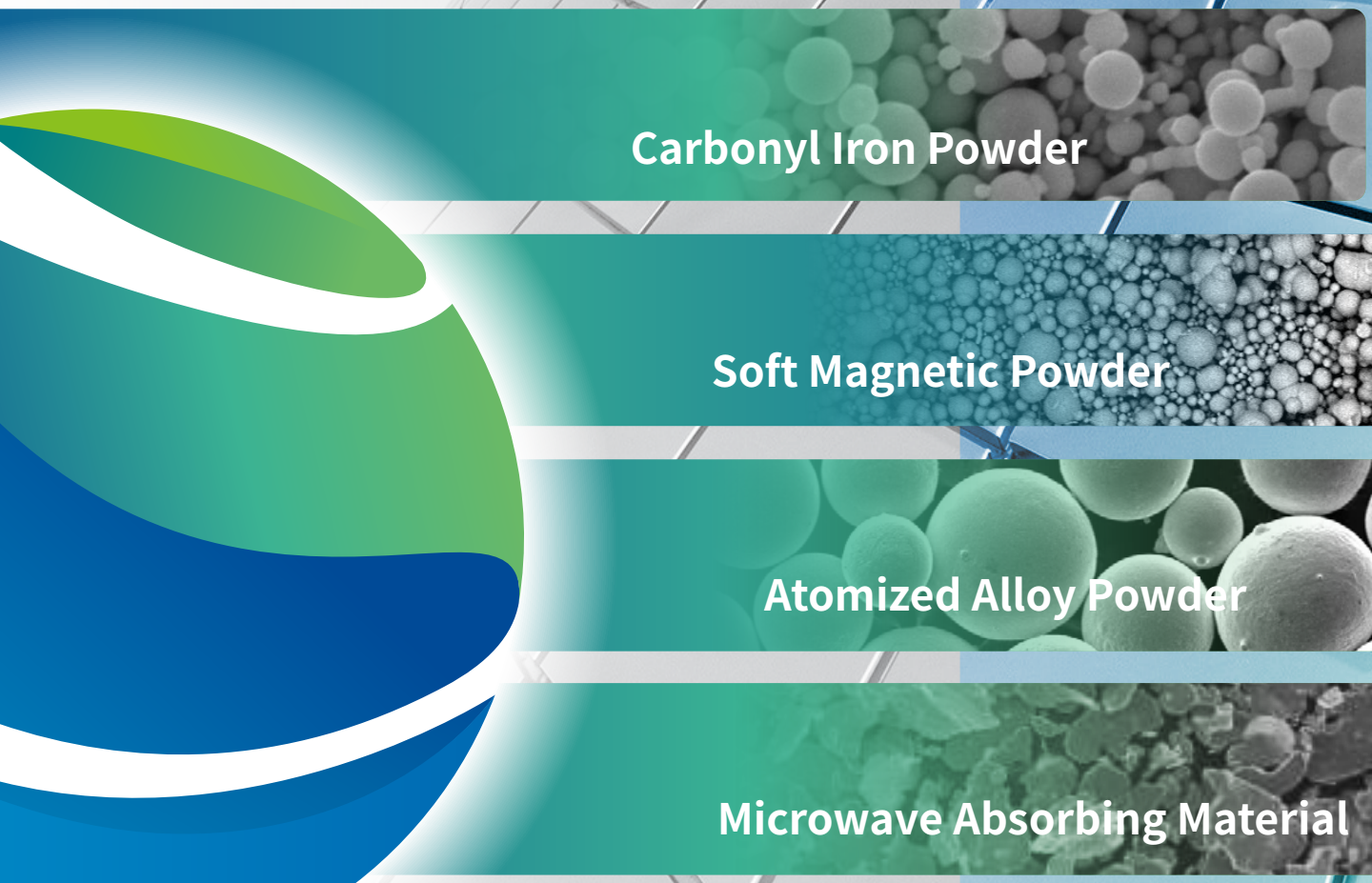

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Metal Injection Moulding of magnesium alloy WE43 for biomedical applications

Magnesium alloy WE43 is a high-strength, lightweight alloy developed in the 1980s containing rare earth (RE) elements including: yttrium (Y), neodymium (Nd) and gadolinium (Gd). The relatively-high solubility, the small difference in electrode potentials, and the passivation effect of the RE elements in the WE43 alloy considerably improve its resistance to oxidation and corrosion, making this alloy one of the few biodegradable metals that have achieved clinical applications.

However, whilst conventional manufacturing processes such as casting and extrusion have been used to produce regular shaped components from WE43 for biomedical applications, they are often not economic for customised, patient-specific, complex shapes having the required strength, ductility and corrosion properties. Here binder-based processes such as Metal Injection Moulding, and also sinter-based Additive Manufacturing (AM), have been shown to have the potential to produce complex near net-shape parts such as biodegradable WE43 alloy bone screws, vascular stents and surgical implants in high numbers and with high reproducibility.

Researchers at the Helmholtz-Zentrum Hereon GmbH, Geesthacht, Germany, and the Christian Albrechts University in Kiel, Germany, have been focusing on the use of MIM to produce Mg WE43 alloy components for biomedical applications, and the results of their work have been published in a paper by M Wolff, E Nidadavolu, W Limberg, T Ebel, and R Willumeit-Römer in *Key Engineering Materials* Vol. 967, December 12, 2023, pp 157-164.

The authors of the paper believe that this was the first time MIM has been used to produce components from the Mg WE43 alloy and, from their published results, it was shown that sufficient strength and elongation at fracture could be obtained using the MIM process.

The feedstock was based on a gas atomised spherical magnesium WE43 alloy powder having particle size below 45 µm, which was mixed with different binder components as shown in Table 1. Mixing was done under protective inert gas atmosphere (argon) to prevent any oxygen uptake in the feedstock. The Mg WE43 alloy feedstock was then injection moulded to produce green dogbone tensile test specimens. The green parts were solvent debound in hexane at 45°C for 900 min to remove the wax binder and stearic acid, leaving only the proprietary PPcoPE polymer as the backbone binder in the brown parts to retain their shape during thermal debinding and sintering. The PPcoPE binder was removed in a combined thermal debinding and sintering furnace using a separate binder precipitation zone. Final sintering was done under high purity argon at 640°C for 64 h. The residual porosity of the as-sintered WE43 material was 1.3% ± 0.1%.

The sintered MIM Mg WE43 alloy parts were then subject to solid solution heat treatment (T4) at 540°C for 26 h, followed by precipitation sinter-hardening heat treatment (T6) at 227°C for 32 h. The mechanical properties of the Mg- WE43 material in the as-sintered, T4 and T6 heat treated condition, are shown in Table 2. With additional T4 and T6 heat treatment after sintering, the MIM Mg WE43 alloy could achieve enhanced material properties with

Binder component [wt.%]	Abbreviation	Manufacturer
Paraffin wax (50 wt.%)	PW 58	Merck
Paraffin wax (10 wt.%)	PW 57	Merck
Stearic acid (5 wt.%)	StA	Merck
Polypropylene-copolymer-polyethylene (35 wt.%)	PPcoPE	--*
** Manufacturer cannot be named due to proprietary interests*		

Table 1 Binder materials used for magnesium Mg WE43 MIM feedstock (from the paper 'Binder based processing of Magnesium Alloy WE43 towards Biomedical Application using Metal Injection Moulding (MIM)' by M Wolff, et al, Key Engineering Materials Vol. 967, December 12, 2023, pp 157-164)

Heat treatment condition	Yield strength (YS) in MPa	Ultimate tensile strength (UTS) in MPa	Elongation at fracture ε %	No. of specimens
as sintered	110 ± 2.2	200 ± 1.6	10.6 ± 1.6	n = 5
T4	102 ± 1.6	196 ± 6.6	11.9 ± 2.5	n = 5
T6	131 ± 7.1	226 ± 5.6	7.6 ± 0.9	n = 5

Table 2 Material properties of WE43 dogbone shape tensile test specimen in the as-sintered (asS), T4 and T6 condition (from the paper 'Binder based processing of Magnesium Alloy WE43 towards Biomedical Application using Metal Injection Moulding (MIM)' by M Wolff, et al, Key Engineering Materials Vol. 967, December 12, 2023, pp 157-164)

ultimate tensile strength (UTS) of 226 MPa at 7.6% elongation at fracture. This compares with 250 MPa UTS, 160 MPa YS and only 2% elongation in T6 chill cast WE43 alloy.

The authors found that diffusion of the yttrium, gadolinium and neodymium alloying elements in the magnesium matrix of the as-sintered MIM WE43 material during T4-solid solution heat treatment could not be performed satisfactorily, leading to slightly lower mechanical properties but increased elongation. This might be due to the oxide layer hindering the diffusion of the alloying elements into the α Mg-matrix within the given time for T4 heat treatment. The incomplete T4 heat treatment showed that T6 precipitation hardening could not then be fully performed and that the final WE43 microstructure still contained coarse secondary phases as shown in the SEM images in Fig. 1(a) and Fig. 1(b). Nevertheless, mechanical tensile testing of the MIM WE43 alloy still proved the overall beneficial effect of T4 and T6 heat treatment on the UTS, YS and elongation results shown in Table 2.

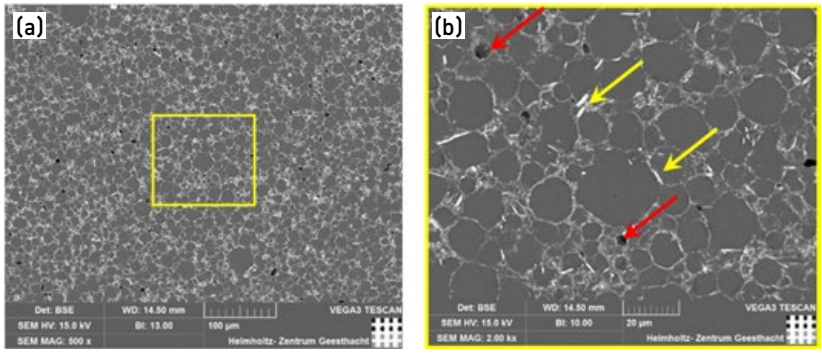

Fig. 1 (a) SEM image of WE43 microstructure in the as sintered + T4 + T6 condition; (b) higher magnification of the central area of Fig. 1(a) showing unexpected bright coarse grain boundaries and needle shape secondary phases at low residual porosity (from the paper 'Binder based processing of Magnesium Alloy WE43 towards Biomedical Application using Metal Injection Moulding (MIM)' by M Wolff, et al, Key Engineering Materials Vol. 967, December 12, 2023, pp 157-164)

The authors plan to carry out further investigations into the question of inhibited solid solution ability of the alloying elements yttrium and gadolinium during T4 heat treatment, and will also investigate the introduction of the magnesium WE43 alloy powder for sinter-based Additive Manufacturing.

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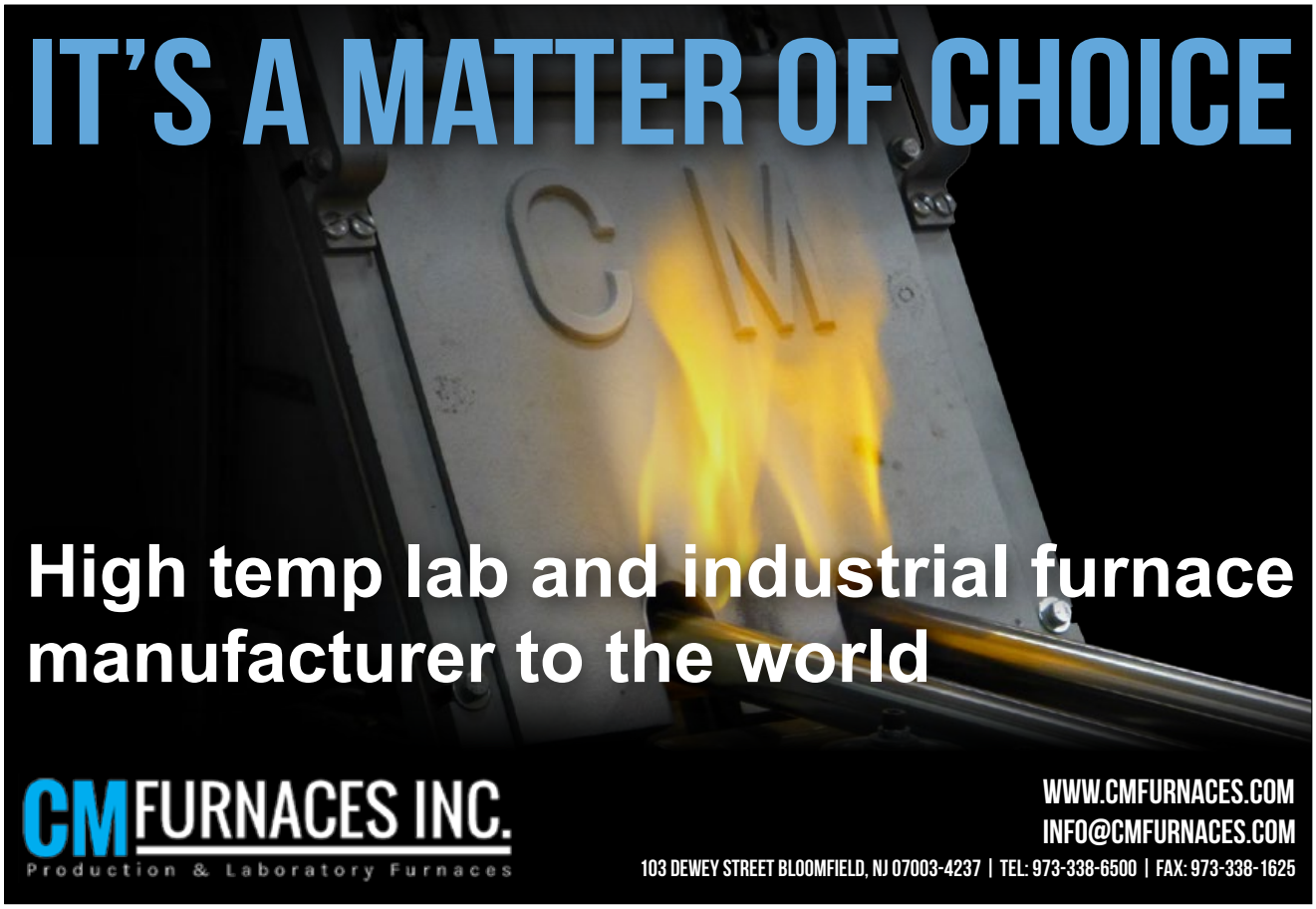

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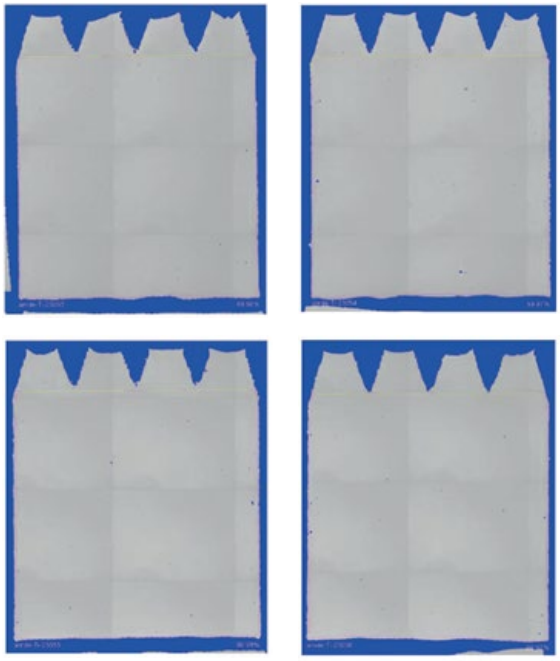
— JSJW TITANIUM —

Since its establishment in 2018, JSJW New Materials Co., Ltd., has been exploring the production processes of titanium alloy powders, relying on its independently developed IPCA technology, which has distinct advantages in yield rate and production capacity. In metallographic analysis, samples printed with JSJW New Material TC4 powder showed a density exceeding 99.98%, indicating excellent performance in all aspects.

At TCT Asia 2023, JSJW New Materials showcased Ti alloy powder solutions that are compatible with Electron and Laser Powder Bed Fusion, Binder Jetting, and MIM technologies and applications in aerospace, orthopaedics, dental and 3C products. At the event, our outstanding 3D printed Ti components attracted a lot of attention both on- and offline.

We look forward seeing you on **Booth 12.0 E38 at FORMNEXT 2023** in November, where we can explore titanium alloy solutions tailored to your needs.



Density	SPL_1(23053)	SPL_2(23054)	SPL_3(23055)	SPL_4(23056)	Avg	DOM (≥99.90%)
	99.98%	99.97%	99.98%	99.97%	99.98%	OK

TC4

Note: The information is provided by a third party medical customer.
Test results might subject to test methods. Please contact us for further information.

Chemical Composition		O	N	H	C	Fe	Al	V	D10	D50	D90	Density
Receiving Standard	<	0.1	0.03	0.008	0.08	0.25	5.5~6.5	3.5~4.5	22~32	34~44	49~61	/
JSJW	Powder	0.08	0.003	0.003	0.02	0.15	5.8	4.2	24.2	36.6	55.6	2.46
	Parts	0.14	0.04	0.001	0.02	0.15	5.87	4.3				
A Foreign Brand	Powder	0.082	0.006	0.002	0.02	0.17	6.05	3.778	24.5	36.9	54.6	2.28
	Parts	0.11	0.034	0.0013	0.032	0.18	5.92	3.92				

Typical Mechanical Properties	Tensile Strength (Mpa)	Yield Strength (Mpa)	Elongation (%)	Reduction of Area (%)	Density (g/cm³)	Hardness (HV10)
≥	895	825	10	25	4.40	/
JSJW	1072	1010	16.2	48.8	4.52	355
A Foreign Brand	1080	1033	17.1	37.4	4.51	/

Finished Fusion Mechanical Properties	Stiffness/MPa	Yield Load/MPa	Max Load/MPa
JSJW	79045	37098	45099
A Foreign Brand	66958	28952	35887

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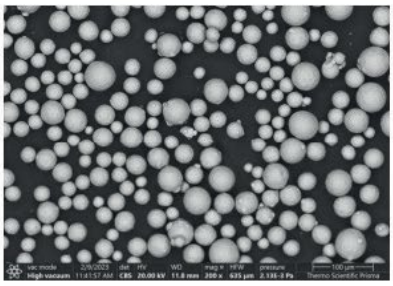

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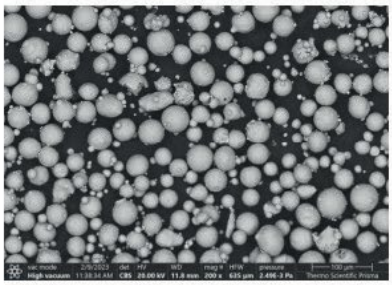

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High-oxygen MIM Ti-6Al-7Nb alloys with high tensile and fatigue properties

Although Metal Injection Moulding offers many advantages compared with other manufacturing processes in terms of near-net shape and good or very good mechanical properties for titanium alloy components, the production of high performance Ti alloy parts by MIM remains challenging.

One of the key issues with MIM Ti alloys is the uptake and control of interstitials and the development of a dedicated MIM Ti alloy, which is robust against high interstitial levels but still meets the requirement for strength and ductility, would greatly enhance the industry's acceptance. Such a dedicated Ti alloy would additionally be attractive for Laser Beam Powder Bed Fusion (PBF-LB), Binder Jetting (BJT) and other Additive Manufacturing processes where economical powders with higher oxygen content could be used.

Research has been underway at the Helmholtz Zentrum Hereon, Geesthacht, Germany, in collaboration with Höganäs AB, Sweden, and the University of Applied Sciences and Arts Western Switzerland, Sion, Switzerland, to evaluate Ti-6Al-7Nb as an alternative to the Ti-6Al-4V alloy commonly-processed by MIM. The results of this research were published in a paper entitled: 'High-oxygen MIM Ti-6Al-7Nb: Microstructure, tensile and fatigue properties', by A A Hidalgo, T Ebel, R Frykholm, E Carreño-Morelli, and F Pyczak, in *Materials Today Communications*, Vol. 34, 2023, 104982, 10pp.

The authors stated that MIM Ti-6Al-7Nb was selected as an alternative to Ti-6Al-4V because of its slightly better biocompatibility resulting from the replacement of vanadium by niobium, and that the microstructures and mechanical properties of both alloys are very similar. Their focus in this research was, therefore, to understand the influence of oxygen on the tensile and high cycle fatigue (HCF) properties of Ti-6Al-7Nb processed by MIM and whether oxygen could purposely be used as a potent strengthener. The authors also aimed at establishing correlations between crystal structure and microstructure, and the tensile behaviour and HCF properties of sintered MIM Ti-6Al-7Nb specimens. Special attention was given to ascertain if excessive amounts of oxygen might cause a dramatic drop of ductility due to deformation mode changes and the evolution of non-equilibrium microstructures.

Two gas atomised spherical Ti-6Al-7Nb powders were produced in-house at Helmholtz-Zentrum Hereon: one using the PIGA technique (plasma induction melting guiding gas atomisation); and the other using a commercially extruded rod material by the EIGA technique (electrode induction melting gas atomisation). The interstitial contents of PIGA powders were 0.098 wt.% O, 0.002 wt.% C and 0.003 wt.% N, while EIGA powders contained 0.211 wt.% O, 0.004 wt.% C and 0.007 wt.% N. In both cases, the powder was sieved to −45 µm. The EIGA and PIGA produced Ti-6Al-7Nb powders were mixed with a multicomponent binder consisting of 35 wt.% ethylene vinyl acetate, 60 wt.% paraffin wax and 5 wt.% stearic acid. The powder loading was 64.5 vol.%.

The MIM Ti-6Al-7Nb feedstock was injection moulded to produce parts with low oxygen for standard tensile testing and also four-point bending fatigue testing. In order to analyse specimens with higher oxygen content (up to 0.61 wt.%), parts produced with the EIGA powders were first subjected to a pre-sintering step, followed by thermal treatment during which the specimens were exposed to an oxygen (20%)-argon atmosphere of 1 bar with flowing gas, and then finally sintered at 1,350°C for 4 h under high vacuum. The sintered MIM Ti-6Al-7Nb specimens exhibited around 3% of residual porosity. The authors reported no significant difference in residual porosity or shrinkage in specimens with different oxygen contents or different shape. The interstitial contents of the sintered MIM Ti-6Al-7Nb parts for tensile and fatigue testing are shown in Tables 1 and 2 respectively. The higher oxygen content was acquired when the speci-

Tensile specimens	Thermal treatment time [min]	Oxygen [wt.%]	Nitrogen [wt.%]	Carbon [wt.%]
PIGA	No treatment	0.13	0.00	0.02
EIGA	No treatment	0.20	0.03	0.03
	0–900	0.24–0.61	0.01–0.03	0.03–0.05

Table 1 Interstitial contents of MIM Ti-6Al-7Nb tensile specimens (from the paper 'High-oxygen MIM Ti-6Al-7Nb: Microstructure, tensile and fatigue properties', by A A Hidalgo et al, in Materials Today Communications Vol.34, 2023, 104982, 10pp)

Fatigue specimens	Thermal treatment time [min]	Oxygen [wt.%]	Nitrogen [wt.%]	Carbon [wt.%]
PIGA	No treatment	0.15	0.01	0.02
EIGA	No treatment	0.26	0.01	0.03
	0–900	0.30–0.59	0.01–0.04	0.03–0.06

Table 2 Interstitial contents of MIM Ti-6Al-7Nb fatigue specimens (from the paper 'High-oxygen MIM Ti-6Al-7Nb: Microstructure, tensile and fatigue properties', by A A Hidalgo et al, in Materials Today Communications Vol.34, 2023, 104982, 10pp)

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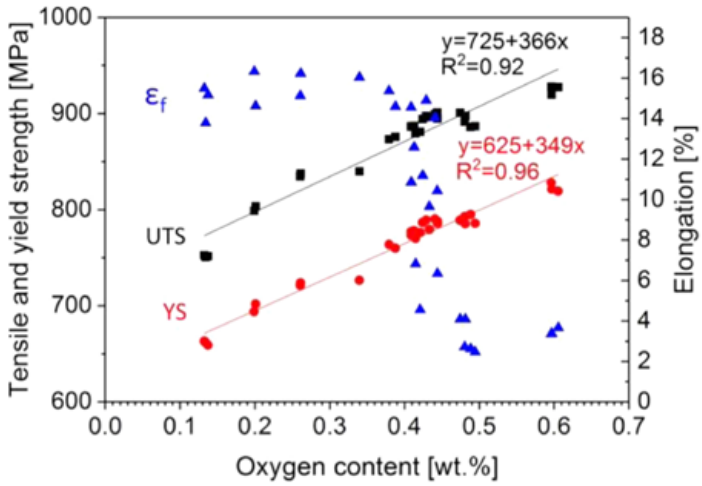

Fig. 1 Influence of oxygen on tensile and yield strength of MIM Ti-6Al-7Nb (from the paper 'High-oxygen MIM Ti-6Al-7Nb: Microstructure, tensile and fatigue properties', by A A Hidalgo et al, in Materials Today Communications Vol.34, 2023, 104982, 10pp)

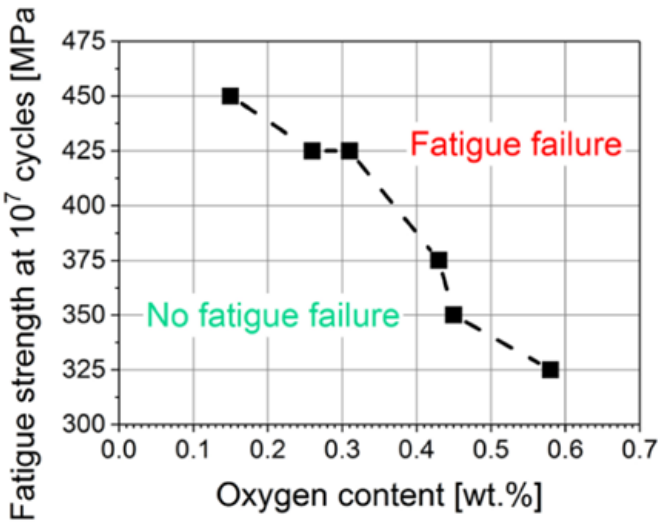

Fig. 2 Influence of oxygen on the fatigue strength of MIM Ti-6AL-7Nb after 10^7 cycles (from the paper 'High-oxygen MIM Ti-6Al-7Nb: Microstructure, tensile and fatigue properties', by A A Hidalgo et al, in Materials Today Communications Vol.34, 2023, 104982, 10pp)

mens were exposed longer under the oxygen-argon atmosphere during presintering.

The sintered MIM Ti-6Al-7Nb alloys were subject to tensile testing on a servo-hydraulic system equipped with a 100 kN load cell at a strain rate of 1.2 × 10− $5^{1/s}$ at room temperature in air. High cycle fatigue (HCF) testing was done in a four-point bending fixture in air at room temperature. The surface of the sintered MIM test parts was shot peened prior to HCF testing in order to introduce compressive residual stress, improving the HCF strength. The maximum number of cycles was established at 10^7 cycles to define the fatigue life. Selected low-oxygen specimens and high-oxygen specimens were subjected to a HIP treatment at 920°C in argon atmosphere at 1,000 bar for 120 min to study the slip behaviour.

The authors reported on the properties achieved after tensile testing and the different mechanisms by which oxygen impacts the tensile behaviour of the MIM Ti-6Al-7Nb alloy. As can be seen in Fig. 1, oxygen addition improves tensile and yield strength. A significant drop in ductility was found at 0.38 wt.% of oxygen. Fig. 2 shows the dependency of fatigue strength on oxygen content after 10^7 cycles. It shows that fatigue resistance of MIM Ti-6Al-7Nb is continuously reduced with increasing oxygen content, but, in contrast to ductility, there is no visible sudden decrease at a specific oxygen level. Similar to tensile behaviour, interstitial oxygen has an impact on important factors related with the HCF behaviour.

This study supports the use of oxygen as an alloying element in MIM α + β titanium alloys for improving tensile strength without excessive loss of either ductility or HCF properties. However, special attention has to be paid if using an excessive amount of oxygen that might cause a dramatic drop of ductility due to deformation mode changes and evolution of non-equilibrium microstructures. The authors have determined that such a non-equilibrium microstructure contributes to strengthening and loss of ductility, but that it can be controlled by using an optimised cooling rate during the sintering cycle.

These findings support the use of oxygen as an alloying element in MIM α + β titanium alloys for strengthening without excessive loss of either ductility or HCF properties. Hence, the efforts to control the uptake of oxygen during MIM processing could be minimised thanks to the tolerance of the Ti alloy to oxygen in relation to mechanical properties.

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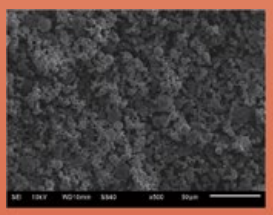
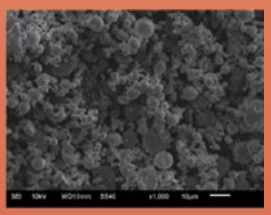
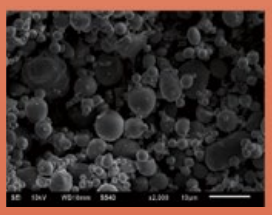
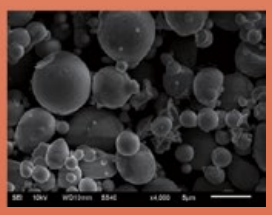
Item	T.D(g/cm^3)	S.S.A(m^2/g)	S.D(g/cm^3)
316L	4.8	0.34	7.9
17-4PH	4.7	0.34	7.7
304L	4.8	0.34	7.8
HK30	4.7	0.34	7.7
4J29	4.9	0.34	7.95
F75	5.0	0.34	8.1

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INMATEC Technologies: Celebrating 25 years as a driving force behind Ceramic Injection Moulding

For twenty-five years, INMATEC Technologies GmbH has been producing market-leading feedstocks for both Ceramic Injection Moulding (CIM) and Metal Injection Moulding (MIM). Dr Georg Schlieper recently visited the company for *PIM International* and, in this article, reports on its history, current activities and expectations for the future of engineered ceramics. What is clear is that following strategic investments from luxury goods house Chanel, which now owns a majority stake in the business, the future for CIM and ceramic Additive Manufacturing looks brighter than ever.

The small town of Rheinbach, in the vicinity of the former German capital, Bonn, is the headquarters of INMATEC Technologies. The company was formally established in 1998 and, in the same year, its feedstock compounding technology and quality assurance systems were developed. It was, however, in early 1999 that commercial operations began and the first 500 kg of feedstock was delivered. Twenty-five years on, this is the date that Dr Moritz von Witzleben, founder and Managing Director of the company to this day, remembers as the true beginning of the company.

From the very beginning, INMATEC was nurtured by von Witzleben and managed in a relaxed and open manner and, still today, the company is characterised by a flat hierarchy. It operates eight production lines for feedstocks for Ceramic Injection Moulding and Metal Injection Moulding and has a team of sixty employees. The company's operations are structured so as to allow it to respond flexibly to customers' special orders and react quickly to changes in the market.

INMATEC's feedstock compounding operations have been based on shear roll extruder technology since the beginning, in contrast to many other companies in the industry who often worked with sigma or Z-blade mixers. In close cooperation with Dr-Ing A Albers, the inventor of the shear roll extruder, the extruders were adapted to meet INMATEC's specific requirements so that, by the end of 1998, the

Fig. 1 Chanel's J12 ceramic watches are amongst the highest profile examples of CIM in the luxury sector. Today, Chanel SAS holds a majority stake in INMATEC (Courtesy Chanel/INMATEC)

Fig. 2 The most important piece of equipment in feedstock production: the shear roll extruder (Courtesy INMATEC)

company's first high-quality ceramic feedstock was ready for production. Commercial production began in the Start-up and Technology Centre in Rheinbach. Initially, the INMAFEED feedstocks were produced using a commercially available binder system.

Von Witzleben spoke very openly to *PIM International* about the fact that the history of INMATEC has been characterised by periods of extreme growth and hard setbacks, especially in the early years. In its first year of commercial operations, an automotive supplier that manufactured ignition plug insulators using CIM caused a surge in demand for feedstock, necessitating a second production unit to be quickly put into operation to meet demand.

"The production of CIM feedstocks for luxury goods, such as watch cases and bracelet parts, began in 2006. These applications not only required strength and hardness, but also needed to meet extremely high aesthetic requirements."

This was followed by the 'ferrule hype', as von Witzleben called it. Ferrules are fine ceramic tubes used to connect fibre optic cables. As early as 1999, von Witzleben secured customers in Taiwan, Europe and the USA, and tools and an entire production line for ferrules was developed. "With the collapse of the dotcom bubble in 2001, business with Taiwan suddenly collapsed, our bills were no longer paid, and INMATEC had to file for bankruptcy to get out of debt," he said. "After the restart, INMATEC focused purely on the production of ceramic feedstock and the provision of technical support to customers."

In 2001, the company moved into its current headquarters in Rheinbach. After a short time, the demand from a prominent customer increased very quickly. The production of CIM feedstocks for luxury goods, such as watch cases and bracelet parts, began in 2006. These applications not only required strength and hardness, but also needed to meet extremely high aesthetic requirements.

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The company survived the 2008 financial crisis relatively unscathed and, by 2012, was operating four feedstock production lines. However, a slump in the luxury watch industry, which, by now, was a major buyer of ceramic feedstock, negatively impacted the business.

In 2013, the product range was further expanded to include feedstock for translucent ceramics. The in-house developed binder system for the company's INMAFLOW feedstocks was introduced in 2014, followed by the INMAPOM system in 2017.

In 2017, four major customers concurrently increased their orders. In order to meet the sudden increase in demand, feedstock production was increased to a record level. New solutions had to be found to produce feedstock of consistently high quality on an industrial scale. Under great pressure, feedstock was produced day and night. "The COVID-19 pandemic then gave us a breathing space that we desperately needed," von Witzleben stated. By 2020, the production capacity was expanded to the current eight production lines.

By 2012, the privately owned French luxury goods company, Chanel SAS, had acquired a 10% stake in INMATEC. Chanel's interest was to secure the supply of the raw material for its luxury ceramic watches, as a sales volume of many millions of euros depended on it. "Every year since 2015, several other interested parties expressed interest in buying a stake in INMATEC," von Witzleben said. "Finally, in 2021, we agreed to Chanel taking a majority stake in the business." Chanel's support gave INMATEC the freedom to supply other customers and further develop the market. Von Witzleben still holds a minority stake in the company.

The company's history has shown that – at least in the early years of CIM technology – opportunities and risks in the industry were closely linked to specific products. Over time, however, a stable and more diversified market for CIM parts has developed, protecting the business from the ups and downs of the early years.

Dr Moritz von Witzleben, founder of INMATEC Technologies (Courtesy INMATEC)

Moritz von Witzleben's wider role in promoting the adoption of engineered ceramics

The von Witzleben family is one of the oldest noble families in Germany (an ancestor of the von Witzleben family was first mentioned in a document in 1133). Moritz von Witzleben was born in 1968 in the United States and holds dual German and American citizenship. At the age of five, he moved to Germany with his parents. He studied mineralogy at university and, through his doctoral thesis, became acquainted with technical ceramics and the then-growing Ceramic Injection Moulding process. Recognising the industry's emerging need for customised feedstocks, he decided to become an entrepreneur in this sector.

In addition to managing INMATEC, von Witzleben is particularly concerned about the education and training of young people. As chairman of the family foundation, he is responsible for the management of the Rossleben boarding school in Thuringia, which was founded in 1554 by one of his ancestors. He also works as a lecturer at the universities of Höhr-Grenzhausen and Bonn-Rhein-Sieg, where he lectures on materials engineering, with CIM technology having a special emphasis, and supervises student theses, some of which are carried out in his company.

"If we don't support our young people in their education in the best possible way, they won't be able to solve our social challenges," he stated. "That's why it's our job, especially for engineers at the end of their careers, to pass on their knowledge and thus create the best conditions for our young talent."

Von Witzleben holds numerous further honorary positions. He is a representative of the Board of Directors of the German Ceramic Society (DKG) and the European Ceramic Society (ECERS). As a board member of the German-language 'expert group' for Ceramic Injection Moulding, he participates in regular exchanges with industry colleagues and research institutes.

Fig. 3 INMATEC supplies ceramic feedstocks to customers all over the world (Courtesy INMATEC)

Fig. 4 Embemould wax-based binder for INMAFEED feedstocks (Courtesy INMATEC)

Sales and logistics

Increased production volumes have not only brought about major changes in the company's manufacturing operations but also in sales and logistics. While in the past, customer contacts were mainly made at the engineering level, purchasing professionals, whose task it was to drive down supplier costs, came onto the scene. "This came as a complete surprise to us," said Karin Hajek, who is responsible for sales and logistics. "It took us a certain amount of time to adjust to these conditions."

The company has all the necessary equipment for the full Ceramic Injection Moulding process installed at its facility, from injection moulding to debinding and sintering, enabling it to effectively support customers in product development. Over the past twenty-five years, it has naturally accumulated a lot of experience and expertise in all areas of the CIM process, and a comprehensive training programme is now available for customers.

Ceramic feedstocks are supplied to customers all over the world. Over the past two years, sales agents in Eastern Europe and South America have been added to support sales activities. A key factor in the selection of these agents was the fact that they were already active in the MIM sector and knew the technology very well. This provided a good basis for training in the specifics of CIM technology. As a result, these sales partners have been able to effectively penetrate these markets.

North American customers are still served directly from Germany but, in the foreseeable future, a sales agent will also take over responsibility for North America. In the short term, von Witzleben expects the greatest growth potential in North and South America. Of course, the Asian market is also significant, but it comes with great risks. For this reason, the company is currently undertaking only minor activities in the region.

Customer service at the heart of the company's success

"An essential basis for our success is the close and trusting cooperation with our customers on a technical level," Hajek noted. "Our hands-on experience helps us to support our customers in solving their technical problems. Based on our many years of experience, we can effectively assess whether a new customer with little or no CIM experience will be able to effectively integrate the technology into their production. When receiving part enquiries, we are able to recommend existing clients as experienced and reliable producers."

The ceramics industry is characterised by many specialities requiring a great deal of specific expertise. For this reason, the company manufactures a large number of bespoke customer formulations which have been developed together with customers for specific products. According to Hajek, only about 20% of the production is standard feedstocks; INMATEC also offers toll processing of feedstock in case customers want to use their own material and binder system.

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Fig. 5 Binder, powder, and feedstock pellets (Courtesy INMATEC)

Binder systems for INMATEC feedstocks

INMATEC offers a variety of binder systems that differ significantly in terms of processing properties. There is a choice of three standard binder systems:

INMAFEED
For the INMAFEED feedstock series, the wax-based Embemould binder system is used. Products manufactured with this binder system require two-stage debinding. In the first debinding step, part of the binder is dissolved in a water bath; this is followed by a thermal debinding step before the parts are heated to sintering temperature.

INMAFLOW
The binder system for the INMAFLOW range of feedstocks is based on polyamide, which gives them particularly good flow properties. The binder was originally developed for Metal Injection Moulding, but INMATEC has adapted it to be used with ceramic powders. Parts that are susceptible to the feedstock freezing during injection moulding can usually be produced flawlessly with this binder system. Debinding is also a two-stage process, first by solvent debinding in an acetone bath and then by a second thermal debinding step.

In addition to its suitability for the production of feedstock granules for MIM and CIM, this binder system is also suitable for the production of filaments for Additive Manufacturing (AM).

INMAPOM
Finally, the company offers a polyacetal-based (POM) binder system under the name INMAPOM. Originally developed by BASF, who has since ceased the production of ceramic feedstocks, this binder is characterised by good processing properties as well as very high green strength and dimensional stability. Since debinding is catalytically carried out in a single step, this system allows for very short processing times that are unmatched by other binder systems.

Quality checks on feedstock cover binder content to ensure repeatable batch-to-batch shrinkage, rheological properties in the injection moulding process, and debinding and sintering behaviour. The extensive experience gained in binder development now enables INMATEC to respond very flexibly to customer requests and offer special solutions if required. Since these three binder systems require different debinding processes, the selection might also be determined by the available equipment installed in a customer's facility.

Fig. 6 Extruded pipe and rod made from INMAPOM (Courtesy INMATEC)

"Over the past ten years, binder development has been a high priority for us, driven in part by the fact that customer requirements, in terms of wall thickness and geometrical complexity, are becoming ever greater."

Sourcing ceramic powders

The ceramic powders used in the company's feedstocks are purchased from leading suppliers to the ceramics industry. "Often, injection moulding requires tighter tolerances for powder characteristics than other ceramic applications," said Hajek. "In the beginning, we had to fight hard to get suitable powders for our technology, but, in the meantime, the ceramics industry has recognised us as a valuable customer and is responding to our needs."

The most common material grades are Al_2O_3 96%, Al_2O_3 99.7% and yttria-stabilised zirconia; however, a wide spectrum of other materials is available.

As part of a quality management system certified according to ISO 9001:2015, all raw materials are subjected to a consistent incoming inspection. More in-depth investigations of chemical composition, phase analysis, particle size or specific surface area are undertaken when required.

Supporting innovation

"Over the past ten years, binder development has been a high priority for us, driven in part by the fact that customer requirements, in terms of wall thickness and geometrical complexity, are becoming ever greater," said Hajek.

In order to intensively advance binder development, the company has a four-person development team incorporating expertise from the chemical industry. Binder development not only relates to the optimisation of binder system composition, but also encompasses all processing steps, from feedstock preparation to injection moulding, debinding, sintering, and any post-treatment to the finished product. These developments are always targeted at a specific application and are carried out in close cooperation with the customer.

Recent developments in injection moulding technology have also been incorporated into the company's development programme. These developments include variotherm injection moulding technology. "This innovative technology enables the production of very large components with a length of up to 200 or 300 mm and a wall thicknesses of less than 1 mm, but our binder systems have had to be adapted for this," said von Witzleben. "This technology can open up new markets for us."

Variotherm technology is based on the principle that the mould cavity should be at nearly the same temperature as the feedstock at the time feedstock is injected. This allows it to fully fill the cavity without freezing on cold walls. Once the cavity is filled, the mould is cooled as quickly as possible so that the moulded part solidifies and can be removed. Before the next injection, the cavity is quickly heated up again.

In order to put the rapid heating and cooling of the cavity into practice, effective heat exchangers must be created close to the contours of the cavity. Innovation surrounding the control of injection moulding machines is also opening up new

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possibilities for the characterisation of feedstocks in relation to specific components. As a result, part quality and overall process capability can be taken to a higher level.

Simulation of the injection moulding process is used by INMATEC's customers to optimise mould design. However, von Witzleben's opinion is that this software is not yet mature enough to really be solely relied upon; the experience of the tool designer is still crucial. Current developments in the field of Artificial Intelligence (AI) are, however, being closely monitored. According to von Witzleben, AI can help to better understand what happens in the feedstock during preparation and processing.

The company's management has a strong focus on sustainability. Measures are taken to minimise environmental impact, avoid waste, and reduce raw material and energy consumption. Only electricity from renewable energy sources is used, and reusable containers are employed in shipping whenever possible. However, von Witzleben points out that the potential for energy savings in powder production is much greater than in feedstock processing. The company, therefore, has close contact with its powder suppliers in order to exploit all possibilities to reduce overall energy usage.

Applications for INMATEC's feedstocks

The company's feedstocks are used in a diverse range of applications. Among the best-known CIM parts are the grinding burrs of fully automatic coffee machines (Fig. 7). The high hardness and wear resistance of the material (99.7% Al_2O_3) is ideally suited for this application. Another component that requires high wear resistance is the nozzle for a high-pressure cleaner (Fig. 8). There are other applications in consumer goods, such as household appliances and textile machinery. The automotive sector, mentioned above, still plays an important role for the CIM industry.

Fig. 7 Grinding media for fully automatic coffee machines (Courtesy Kläger/INMATEC)

Fig. 8 Nozzle for a high-pressure cleaner (Courtesy Kläger/INMATEC)

"Von Witzleben points out that the potential for energy savings in powder production is much greater than in feedstock processing. The company, therefore, has close contact with its powder suppliers in order to exploit all possibilities to reduce overall energy usage."

Fig. 9 An additively manufactured ceramic component produced using CIM feedstock in a pellet-based Material Extrusion machine (Courtesy Pollen AM)

Fig. 10 Additively manufactured tool inserts by Nexa3D which can then be used for low volume CIM - in this case using INMATEC's feedstock (Courtesy Nexa3D)

In medical technology, the biocompatibility of engineered ceramics is a particular requirement. Implants and parts for surgical instruments are partly manufactured by CIM. Dentistry is also seeing an increasing demand for dentures and brackets, some of which are manufactured via CIM.

Aesthetic ceramic applications can be found in the luxury segment of the consumer goods industry: highly sought-after wristwatches, manufactured using white or black zirconia, are among the best-known examples.

The company's CIM feedstocks have also found their way into Additive Manufacturing. AM machines have been developed that can process the same feedstock used in injection moulding technology. In pellet-based Material Extrusion (MEX), the granules are plasticised in micro-extruders and pressed through a fine nozzle and applied, layer-by-layer, to the desired component on a build plate (Fig. 9). Compared to injection moulding, AM not only offers greater design freedom, but also the possibility of producing larger components. Some AM machines offer a build space of 30 x 30 cm or more.

Similarly, the US-based company Nexa3D has additively manufactured inserts that can be used in tooling for low volume Ceramic Injection Moulding (Fig. 10).

Outlook

Von Witzleben sees great potential for the further growth of the CIM industry. Beyond pursuing the success of his own company, he is committed to the advancement of the entire CIM industry. His staff forms a motivated and reliable team that supports him in this task. Through many years of close cooperation with universities and research institutes, von Witzleben encourages a better understanding and further development of CIM technology. In turn, this allows him to stimulate the interest of students in the technology and, as a further benefit, attract talented graduates to join his team.

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A year of change: Turbulence in China's MIM industry as markets evolve

As we start 2024, Greater China's Metal Injection Moulding (MIM) industry is recovering from a perfect storm of challenges. The COVID-19 pandemic didn't only impact operations at MIM plants, but key markets were adversely affected, reducing production volumes. Furthermore, after more than a decade, Apple – China's biggest MIM parts consumer – replaced its Lightning connector, a component which required the production of billions of MIM parts. Dr Q (Y H Chiou) reports for *PIM International* on the changes that are now underway in this, the world's largest MIM producing region.

2023 is now behind us, and that is a good thing! Following on from the COVID-19 pandemic, it was a year of serious challenges for the MIM industry in Greater China. When the sales volume of smartphones – an application that featured numerous MIM parts in unprecedented production volumes – suffered a major decline, the MIM industry as a whole felt the impact. Fortunately, the way this reduction played out gave the industry enough time to find a way out of its slump.

Fig. 1 shows sales figures from the MIM industry in Greater China from 2010 to 2023 alongside Apple's orders for MIM parts. The decline in Apple's orders has, without doubt, affected the sales of MIM in Greater China, but, as shown, the impact gradually decreased. What is the reason for this?

Over a period of twenty days in January, I conducted interviews with multiple MIM companies. Here, I report my findings, sharing some insight into what the industry in Greater China has in store through analysis and discussion of materials, equipment, products and processes. I will also consider how the popularisation of MIM in Greater China has, in turn, led to the advancement of metal Binder Jetting (BJT) Additive Manufacturing.

Materials: MIM powders find a home in AM

No one expected the emergence of metal Additive Manufacturing (AM) to lead to a significant reduction in the price of MIM powder, but that's what has happened. The reason is very

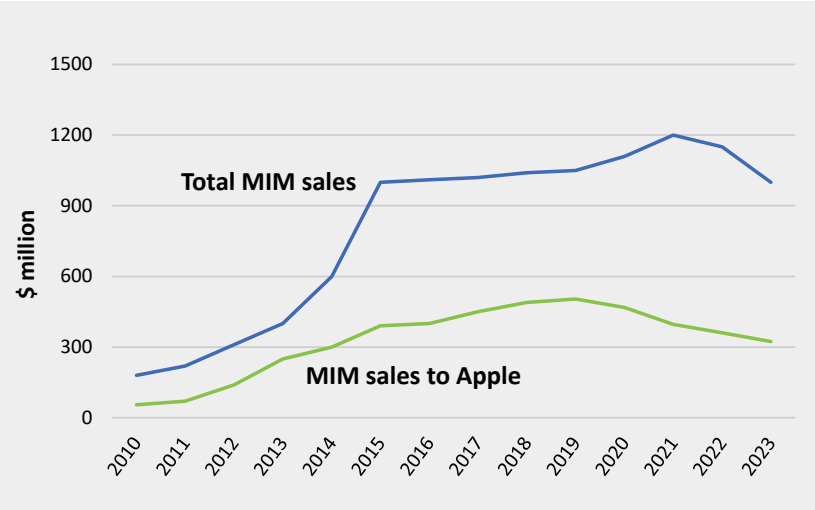

Fig. 1 The relationship between Apple's MIM orders and total MIM sales in Greater China (Courtesy Dr Y H Chiou)

Fig. 2 The camera lens protector on several generations of Apple's iPhones has been made by MIM using CoCrMo alloy (ASTM F75); however this material is now seeing reduced volumes in the smartphone sector (Courtesy Apple)

"According to data from Jiangsu Jinwu New Material Co, Ltd, currently the largest titanium powder manufacturer in China, the growth of titanium powder for AM in 2023 was approximately twice that of the previous year, while the demand for MIM powder more than quadrupled that of the previous year."

simple: powder specifications used by metal AM and MIM overlap. Although most AM technologies require powders with high sphericity, there may be a considerable amount of fine powder left over for MIM production after the spherical powder is taken and used for AM. Material Extrusion (MEX)-based AM, whether using metal-loaded pellets or filament, can even directly use powder grades created for MIM feedstock production. Undoubtedly, these new markets helped MIM powder manufacturers find more business during the drop in the demand for Apple parts.

There are over fifty manufacturers of MIM and metal AM powders in China. These companies make use of different powder manufacturing processes, from gas or water atomisation to other advanced methods. Numerous metals and alloys are available, including ferrous materials, tungsten, titanium, copper, cobalt and nickel.

Stainless steel powders

HL POWDER (Hunan Hualiu New Materials Co, Ltd) is the largest manufacturer of atomised stainless steel powder in China. The company stated that sales of its stainless steel powders (316L/304L/17-4PH) still show growth, with the company providing its MIM grades internationally, including to India. MIM manufacturers have an expectation that powder manufacturers will be able to provide comprehensive powder and feedstock solutions to further improve part quality and reduce material costs.

The rise of titanium

What surprised me the most is the growing demand for titanium and titanium alloy powders. According to data from Jiangsu Jinwu New Material Co, Ltd – currently the largest titanium powder manufacturer in China – the growth of titanium powder for AM in 2023 was approximately twice that of the previous year, while the demand for MIM powder more than quadrupled that of 2022; the overall shipment volume exceeded 200 tons for the whole year (data for pure tita-

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Fig. 3 Sewing machine parts made of MIM 200CY stainless steel have a hardness of HRC49 after sintering (Courtesy CHAOYI)

nium grades TA1, TA2 (using Chinese grading terminology), and TC4 (Ti-6Al-4V)). Titanium alloy powder used by China's MIM and metal AM industries exceeded 800 tons in 2023.

High-strength steels

Although Apple has reduced the usage of MIM parts, resulting in a decreased demand for ASTM F75 powder, the rise of folding smartphones has led to an increase in demand for high-strength tool steel powder. A similar material is also used in other applications, such as nail clippers, kitchen knives, electric clippers, and smart locks. Additionally, I have been involved in the development of MIM 200CY powder from 200 series stainless steel, produced using the large amount of scrap material from kitchen equipment and tools that comes from South China. After sintering, a hardness of HRC 49 can be obtained, opening a new path for MIM recycling. Thus far, the powder has been used to manufacture parts for sewing machines (Fig 3).

"Although Apple has reduced the usage of MIM parts, resulting in a decreased demand for ASTM F75 powder, the rise of folding smartphones has led to an increase in demand for high-strength tool steel powder."

Aluminium and copper: a future with Binder Jetting

For aluminium and copper metal powders, BJT seems to bring a glimmer of hope. In the past, there were concerns about explosivity risks when processing aluminium powder by Laser or Electron Beam Powder Bed Fusion (PBF-LB or PBF-EB, respectively), while aluminium powder MIM feedstock also has some risks associated with it. Copper products were typically believed to have poor outcomes when processed by PBF-LB due to the material's high reflectivity, whereas BJT can manufacture green parts from aluminium or copper and then use MIM sintering technology, followed by CNC machining, to quickly obtain precise samples for prototyping and research. In the case where a part goes into higher volume production, a tool can be manufactured and production ramped up using MIM. In China, BJT and MIM are expected to become closely integrated over the next five years, resulting in the development of entirely new products and mass production.

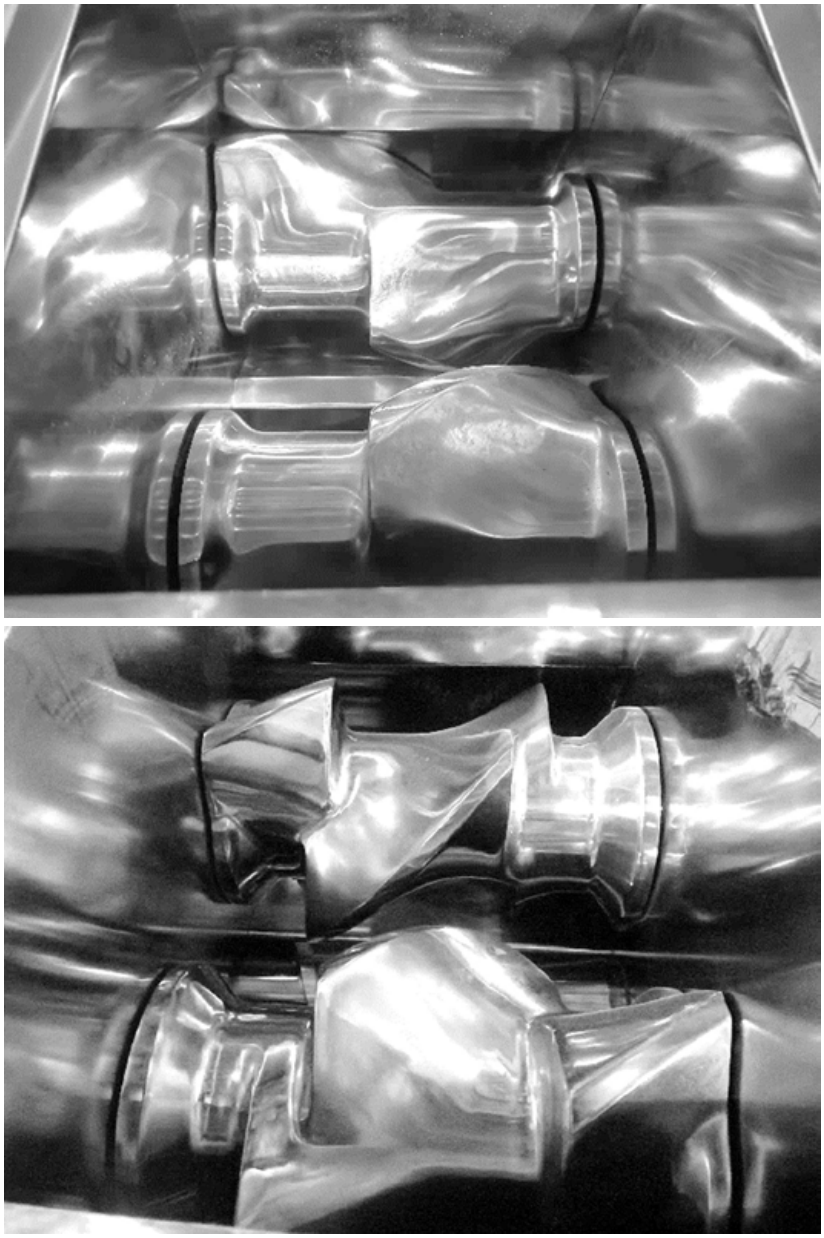

Fig 4. The photo above shows the original two blade mixer, whilst the bottom photo shows a new four blade mixer, part of an integrated machine for mixing and granulation (Courtesy CFine).

"The result was a trend in 2023 of purchasing new equipment to replace the old. The software updates that come along with this new equipment bring updated algorithms, which are more secure, efficient, energy-saving, and convenient to operate."

Innovation in MIM production equipment drives upgrades at part producers

At present, the traditional mechanical parts manufacturing industry in Greater China is facing a lack of a young, skilled workforce. The reluctance of highly skilled young people to enter the traditional mechanical parts manufacturing industry is mainly due to environmental factors – after all, many manufacturing industries have potentially unsafe environments and are associated with higher risks. The development of the MIM industry is also being impacted by this.

Since 2012, I have been promoting Taiwan's MIM expertise within mainland China, leading to MIM equipment manufacturers making marked improvements in the performance of their products. Despite experiencing three years of poor business due to the impact of the COVID-19 pandemic, equipment manufacturers are still optimistic enough to invest in improving their technology. The result was a trend in 2023 of purchasing new equipment to replace the old. The software updates that come along with this new equipment bring updated algorithms, which are more secure, efficient, energy-saving, and convenient to operate – common goals pursued by the MIM industry.

DongGuan CFine Machinery Technology Co, Ltd, has developed and commercialised an integrated four-blade rotor internal mixing/granulation machine, which saw excellent sales results in 2023. In development since 2020, this machines simplifies and automates the mixing and granulation portions of the feedstock production process. The redesigned four-blade rotor can also enhance feedstock density and reduce mixing time (Fig. 4).

Xiamen Throne Vacuum Technology Co, Ltd, has started

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Fig. 5 A high-pressure furnace used for MIM production (Courtesy Throne)

offering high-pressure sintering furnaces, based on the company's own developments, that offer pressures of 1-20 MPa (10 to 200 bar, or 15 to 3,000 psi). These rapid cooling MIM debinding/sintering furnaces move away from the conventional route of using only vacuum or partial pressure atmospheres in batch sintering furnaces for MIM parts (Fig. 5).

Shenzhen SinterZone Technology Co, Ltd, has also expanded its debinding equipment range to include solvent debinding equipment, as well as an integrated debinding and pre-sintering furnace that can operate at up to 950°C (Fig. 6). This solves the problem of green MIM parts being brittle and difficult to move after debinding. It also avoids contamination from binders during the sintering and post-sintering process.

"Shenzhen SinterZone Technology Co, Ltd, has also expanded its debinding equipment range to include solvent debinding equipment, as well as an integrated debinding and pre-sintering furnace that can operate at up to 950°C."

An expanding market for MIM parts

In nearly a decade of consulting work, I have visited at least 100 MIM manufacturing-related companies throughout Mainland China, Taiwan and Japan, including producers of powder, binder, equipment, and parts. Finding parts that are suitable for mass production has always been a challenging task because each MIM company has a different background. A large portion of MIM companies previously focused on plastic injection moulding, but some companies specialised in sheet metal

Fig. 6 A new high temperature debinding and pre-sintering furnace for MIM production from Sinterzone (Courtesy Sinterzone)

processing for metal parts; additionally, some are skilled in the CNC machining of small metal parts. Some companies are also familiar with the manufacturing of geographically specific components or products. In moving to MIM, companies know that the products they are familiar with will do well, whatever the manufacturing technology.

In Guangdong Province, two product blocks can be distinguished from each side of the Pearl River. On the right side of the Pearl River estuary, the cities of Shenzhen and Dongguan focus on electronic products, such as MIM components for smartphones and wearable electronic products. On the other side, in Zhuhai and Yangjiang, there is a focus on household appliances and kitchenware. Using MIM technology to manufacture components for household appliances, as well as kitchen knives and tools, has naturally become a strength in the region. Fig 7 shows a stainless steel 420 nail clipper made by MIM technology, which was produced using the raw material waste of locally forged kitchen knife manufacturers.

"In 2023, more factories were dedicated to making MIM parts than a decade ago, when the market was dominated by parts for smartphones. This reality seems to align with Prof Randall German's prediction that orders offering long-term production are far better than orders for parts that may only have a very short lifespan."

Golf clubs and high-end leather bag fasteners are concentrated in the vicinity of Guangzhou, where larger-sized MIM parts make up the bulk of production. The Yangtze river basin, in eastern China, has different specialities; as a result of the growth of OEM factories for Apple products, the production of MIM parts for these applications has naturally become a focus. In the Zhejiang region, slightly below the Yangtze river basin, magnetic material components and small hardware products are leading MIM manufacturers in two directions. Further north are companies more inclined towards industrial products

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for the automotive industry, textile manufacturing and tools.

In 2023, more factories were dedicated to making MIM parts than a decade ago, when the market was dominated by parts for smartphones. This reality seems to align with Prof Randall German's prediction that orders offering long-term production are far better than orders for parts that may only have a very short lifespan, such as parts for a specific smartphone that may only have a production run of one year.

Integrating assembly operations

MIM requires multiple processes, including powder mixing, feedstock granulation, green part injection, ejection, de-burring, debinding, sintering, and post-processing – and this is without taking the design and verification into account. However, MIM is rarely the sole manufacturing technology for a final application – the technology can almost never meet all the various part requirements of a customer's product. In the past year, I have seen the increasing demand for part assembly in MIM factories. As well as ensuring the dimensional control, surface finish, and aesthetics of MIM parts, manufacturers must now combine them with parts from other processes and/or different materials to achieve the desired results. Combining MIM parts with those produced via Additive Manufacturing is not new. If a MIM parts manufacturer finds their orders dwindling, they are sure to be able to generate more revenue and profits by offering assembly manufacturing.

The stainless steel 420 nail clippers shown in Fig. 7 consist of three MIM parts, a filing strip, and a stainless-steel rotary shaft. Before assembly, each MIM part must be magnetically ground to remove any burrs and surface roughness, then subjected to surface sandblasting, roughening, cleaning, and passivation for corrosion resistance. After installing the shaft, the cutting edge is ground and sharpened before filing strips are applied. Specific trademarks and texts are laser engraved according to customer requirements before they become real consumer products.

Fig. 7 A foldable stainless steel 420 steel nail clipper manufactured using MIM technology. The powder is produced from the scrap of forged kitchen knife production (Courtesy CHAOYI)

> ***"As well as ensuring the dimensional control, surface finish, and aesthetics of MIM parts, we must now combine them with parts from other processes, and parts made with different materials, to achieve the desired results."***

In the past, the production of a nail clipper may have needed to be divided into several factories to complete post-processing, but as competition intensifies, these post-production processes are likely to be brought in-house to the MIM factories themselves. This is expected to become a trend in the future, though, if companies cannot bring the work in-house, the trend may be consistent cross-factory integration, as seen in the Guangdong and Zhejiang regions. This style of cooperation – with an express delivery network to complete the goods – may be an important management technology for the future.

Fig. 8 The end of an era: more than 2 billion Lightning connectors have been manufactured by MIM since 2012, transforming the industry. This application required a huge increase in MIM production capacity in Greater China. In a supply chain carefully managed by Apple, companies such as BASF SE, Arburg GmbH & Co KG and Cremer Thermoprozessanlagen GmbH were key suppliers for feedstock, injection moulding machines, and sintering furnaces, respectively (Courtesy Baurzhan- stock.adobe.com)

"In 2023, Apple finally replaced the Lightning connector, which had been in use for nearly a decade, with the USB-C connector. Produced by MIM, more than 2 billion Lightning connectors have been manufactured."

Crossing a river in the same boat: the first year of cooperation between MIM and Binder Jetting

While metal Binder Jetting is not a new technology, more efficient BJT machines have only emerged in recent years, I was surprised to discover during recent visits that several MIM manufacturers had already invested in BJT and have commercially produced products. Metal BJT, which includes technology from companies such as HP and Desktop Metal, has been used in the launch of a number of different product lines. BJT leverages digital manufacturing to produce a large number of green parts quickly, efficiently and without the need for tooling. However, to densify the powder and form finished metal parts, the help of expertise from the MIM industry is inevitably required. To truly turn metal BJT into a commodity, it needs to follow MIM's commercialised integration process.

Due to the new opportunities opened up by metal Binder Jetting, existing MIM equipment vendors are also starting to launch new products and/or processes, including those focusing on the pre-treatment of BJT powder, the movement and transportation of green parts, more efficient debinding and sintering equipment, etc.

While sintering furnaces currently used in MIM are becoming larger, ranging from 240-600 litres for batch furnaces – and even greater for continuous furnaces – these are not yet applicable to BJT, as BJT is not yet a

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process that produces a very large number of small parts. Therefore, developing small-sized sintering furnaces (<100 litres of sintering space) and changing the cooling process can save sintering energy and time, helping BJT to serve the manufacturing industry more efficiently. I am confident that metal BJT can fully follow the growth model of MIM, and that these technologies will even develop together to become a strong technology combination for powder forming.

The first year after MIM's first half century

In 2023, Apple finally replaced the Lightning connector (Fig. 8), which had been in use for nearly a decade, with the USB-C connector. Produced by MIM, more than 2 billion Lightning connectors have been manufactured. They have provided hundreds of millions of people with a durable and convenient user experience. This part exemplifies the role MIM plays in the modern world - silently serving with little recognition.

A new generation of precision MIM parts is emerging and is rapidly expanding; the lug of Apple watch bands (Fig. 9) used for the quick replacement of smartwatch straps, takes over from the Lightning connector and begins its silent service. Beyond these watch lugs, more MIM components have been developed and continuously used in markets such as energy management, gearing and beyond. I have no doubt that MIM technology will continue to serve all of humanity for another fifty years.

Fig. 9 A new generation of precision MIM parts is emerging and is rapidly expanding, with the lug of Apple watch bands being just one example (Courtesy Apple)

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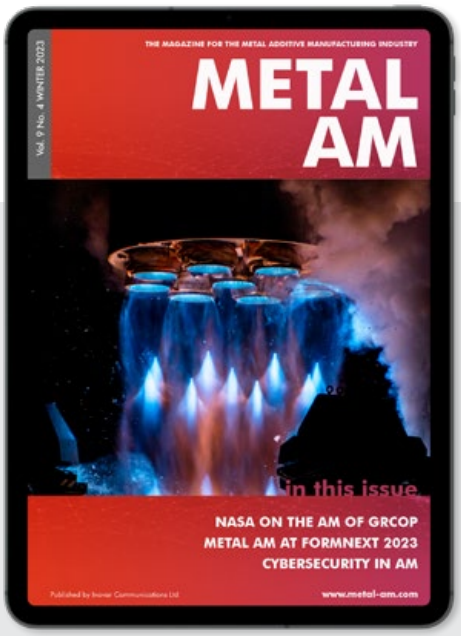

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Ceramic Injection Moulding: The impact of variotherm and conformal cooling technology on part quality and process capability

Despite the success of Ceramic Injection Moulding (CIM) in multiple end-user sectors, from luxury watches to automotive interiors and industrial engineering, there remains considerable scope for process optimisation to advance part quality, productivity and overall process capability. As part of the 'CIM++' research project, Ceramaret, Primaform and the iRAP institute investigated the potential of a variotherm control system for the CIM process and, as the results presented here demonstrate, significant improvements were achieved.

Ceramic Injection Moulding (CIM) is one of the best-known and most widely used processes for the manufacturing of technical ceramics. In contrast to conventional machining techniques, CIM presents notable advantages. It facilitates the production of net-shape components through a single forming step that leverages a substantial degree of design flexibility. Additionally, CIM offers enhanced production volumes and rates, which establishes this technology as a highly competitive process characterised by cost-effective manufacturing practices while maintaining a commensurate level of quality.

However, the high viscosity of ceramic feedstocks during the injection phase – a consequence of the high ceramic powder filling of 50 vol.% or more – in conjunction with high thermal conductivity, poses a challenge in the standard Ceramic Injection Moulding process. The main issue is the rapid solidification of the feedstock during the filling stage when it comes into contact with the cooler mould. Such constraints delineate the feasibility limits of the standard CIM process. Notably, these limitations are conspicuous in the production of high-value components that are characterised by intricate geometries like thin-walled structures in the sub-millimetre range and components featuring fine surface details.

The resultant constraints can cause various quality issues like cracking, deformation, warping and optical defects. These can adversely impact production stability and

Fig. 1 Optimising the Ceramic Injection Moulding process with variotherm technology delivers improvements in process stability and quality. In relation to the manufacture of holographic structures such as this, significant advances in quality and process capability are achieved (Courtesy iRAP Institute, HEIA-FR/HES-SO, Morphotonix)

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Fig. 2 Laboratory for Plastics and Ceramic Injection Moulding at the Institute for Applied Plastics Research (iRAP) in Fribourg. Beside injection moulding, iRAP is active in compounding and recycling, composite materials, material characterisation, surface treatments and nanotechnology. The institute has specific expertise and equipment for Ceramic Injection Moulding and supports industrial partners in the development of innovative products, processes and solutions (Courtesy HEIA-FR/HES-SO)

"This initiative focused on exploring and leveraging the potential of two supplementary technologies: variotherm and conformal cooling, with the aim of improving the capabilities of the Ceramic Injection Moulding process."

robustness and, therefore, lead to substantial scrap rates.

As part of the research project 'CIM++', Ceramaret, Primaform and the iRAP institute (Figs. 2, 3) investigated the potential of a variotherm control system for the Ceramic Injection Moulding process and demonstrated significant improvements.

The CIM++ project's goals

The CIM++ research project was a concerted effort to transcend the aforementioned limitations and enhance the capabilities of CIM technology. This initiative focused on exploring and leveraging the potential of two supplementary technologies: variotherm and conformal cooling, with the aim of improving the capabilities of the Ceramic Injection Moulding process.

Combining CIM and variotherm

To mitigate inherent drawbacks and expand the operational boundaries of CIM, the incorporation of variotherm technology emerges as a compelling prospect. Notably, this technology, prevalent in contemporary plastic injection moulding operations, deviates from conventional injection moulding practices that are characterised by isothermal (constant) mould temperature. The variotherm framework encompasses an enhanced approach through the incorporation of additional heating and cooling stages in the injection moulding cycle.

Compared to standard injection moulding, variotherm mould management is integrated into the injection moulding cycle in the following steps:

1. Heating the mould cavity to a temperature close to the melting temperature of the feedstock
2. Injection, or filling, of the mould cavity
3. Cooling of the mould cavity to the ejection temperature and cooling of the injected part in parallel
4. Ejection of the part

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Various variotherm systems, ranging from fluid-based (water/oil) induction to infrared-based thermal control, are available on the market and address a wide spectrum of industrial applications.

One well-known advantage of variotherm technology for the plastics industry is the resulting enhanced material fluidity, which leads to reduced injection pressure and lower pressure gradients. Furthermore, this allows for an improved filling length from 40-100% greater and, therefore, the production of components with extremely thin wall thickness. The technology significantly enhances the quality and properties of plastic parts, leading to decreased internal stresses, improved control of shrinkage (dimensions), superior quality of weld lines, and exceptional replication of surface micro- and nanostructures [1,2]. However, it is essential to consider certain drawbacks, such as prolonged cycle

Fig. 3 Tristan Rüeger, scientific collaborator at iRAP in the debinding and sintering laboratory (Courtesy HEIA-FR/HES-SO)

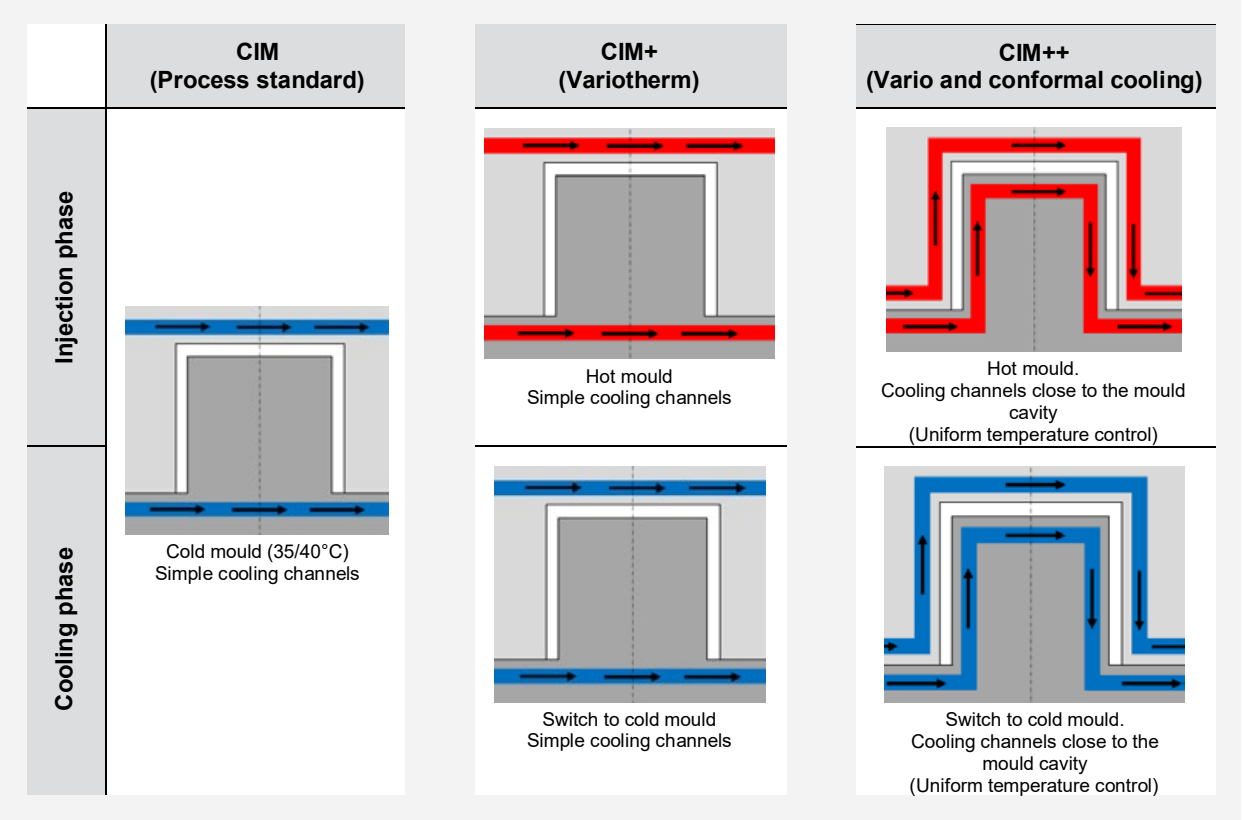

Fig. 4 The strategy of the CIM++project: Left: CIM standard / middle: CIM+, mould with variotherm → heat and cool down / right: CIM++, with variotherm and conformal cooling → cooling channels close to the cavity (Courtesy HEIA-FR /HES-SO, iRAP Institute)

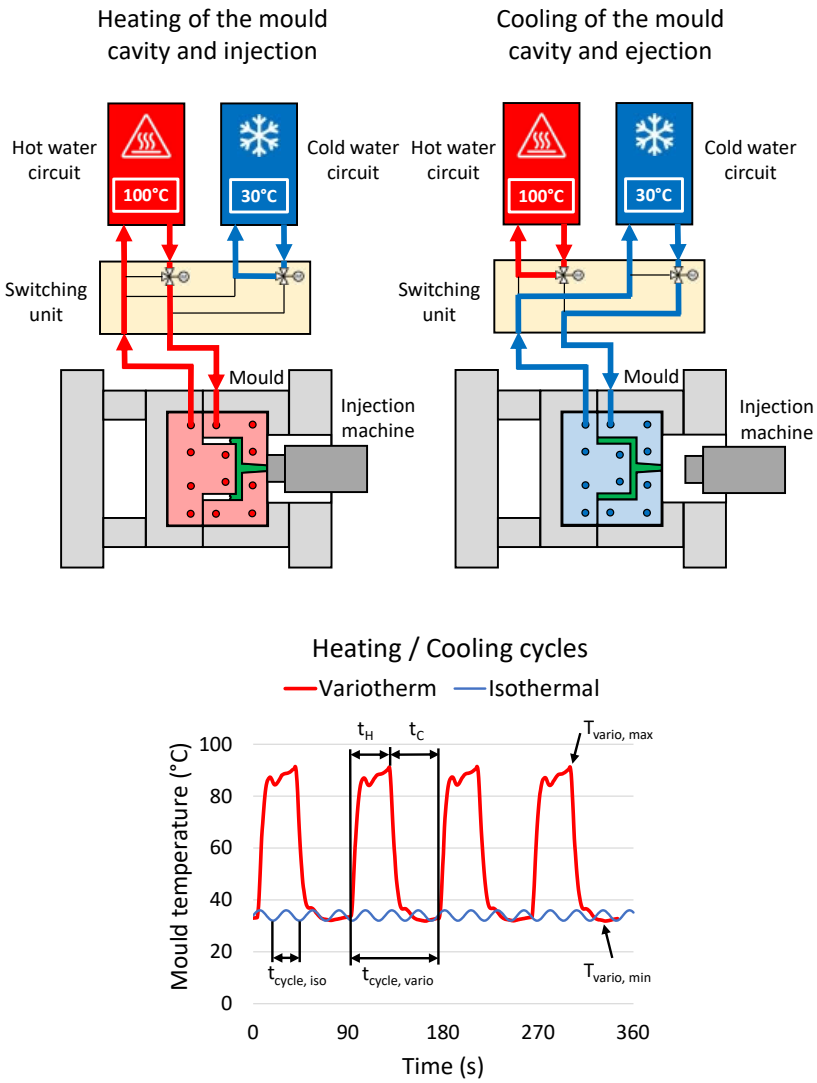

Fig. 5 Schematic representation of a variotherm mould management system with both a hot and a cold-water circuit (top), and a comparison of variotherm (heating and cooling cycles) with an isothermal (constant) mould temperature (below) (Courtesy iRAP Institute, HEIA-FR/HES-SO)

time due to the addition of a heat-up/cooling phase in the mould, higher complexity of the mould design and the need for additional equipment (a variotherm system).

A variotherm system, referred to in this study as CIM+, for the injection of ceramic feedstocks at a mould temperature close to its melting point is promising since this method potentially avoids the aforementioned 'freezing' of ceramic feedstocks with the cold mould cavities. This preventive measure ensures that the feedstock does not undergo excessively rapid cooling during the filling process, thereby enhancing the overall quality of the injection moulded parts.

Combining CIM, variotherm and conformal cooling

In conjunction with the CIM+ solution, the implementation of conformal cooling, referred to in this study as CIM++, proves advantageous for mould cooling systems featuring intricate part geometries. For conformal cooling, the thermal circuit is optimised to achieve a uniformly distributed mould temperature through the close proximity of the circuit to the cavity. This is achieved by fabricating mould inserts using metal Additive Manufacturing (AM), which gives a high degree of design flexibility for a seamless integration of the cooling channels. Unlike traditional machining methods, such as drilling for the creation of cooling

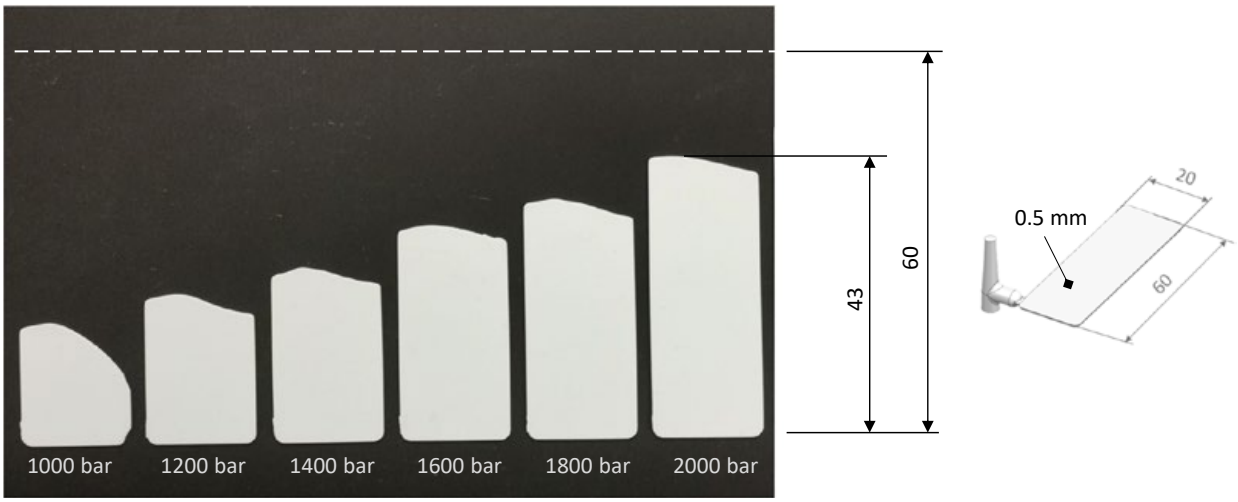

Fig. 6 Filling study of the 0.5 mm plate, with a zirconia feedstock and standard injection moulding conditions (mould temperature 40°C, melting temperature 190°C) (Courtesy iRAP Institute, HEIA-FR/HES-SO)

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channels, this innovative manufacturing approach offers enhanced freedom for the design of mould temperature management systems [3, 4].

The main benefit of conformal cooling systems is the uniform temperature of the mould cavity, which is adapted to complex 3D geometries and prevents the formation of hot spots. Furthermore, it allows for faster cooling, a reduction of the total cycle time by up to 30%, and significantly improved part quality with less part warpage (more uniform shrinkage) and fewer moulding defects (sink marks). The disadvantages are a time-consuming design phase (including simulations), high fabrication costs of the moulds (only justified for large production volumes) and a high clogging risk of the cooling channels that are difficult to clean.

In the CIM++ project, the potential of both variotherm and conformal cooling systems was explored and benchmarked against the standard CIM process. A 'proof of concept' study was conducted in which plates with narrow wall thicknesses (0.3 mm and 0.5 mm) were injected.

Filling study: plate with 0.5 mm wall thickness

The filling study of plates with a wall thickness of 0.5 mm (dimensions: 0.5 x 20 x 60 mm, sintered) showed that injection pressure as high as 1,000 bar or more only achieved a partial filling of the cavity (Fig. 6). By gradually increasing injection pressure it was possible to improve the cavity fill, but, even at 2,000 bar (near machine limits), it was still incomplete.

On the other hand, a repetition of these tests with variotherm (CIM+) applying different mould temperatures (100°C/125°C/140°C) showed that it was possible to completely fill the cavities applying a higher mould temperature of 125°C and a low injection pressure of 800 bar (Fig. 7). A complete fill of the plate was also possible with a lower mould temperature of 100°C, for which an injection pressure of 1,600 bar was needed.

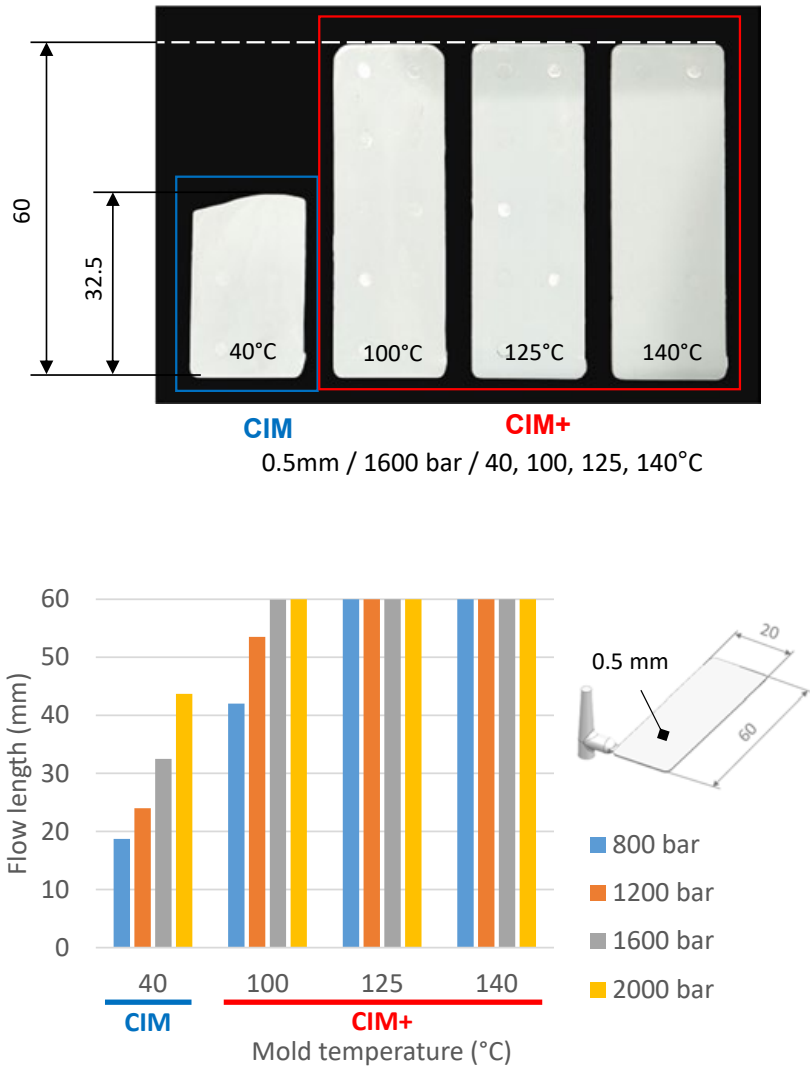

Fig. 7 Filling study of the 0.5 mm plate using a zirconia feedstock and applying standard and variotherm injection conditions (mould temperatures at 40°C/100°C/125°C and 140°C, Melt temperature: 190°C) (Courtesy HEIA-FR (HES-SO), iRAP Institute)

> *"...a repetition of these tests with variotherm (CIM+) applying different mould temperatures (100°C/125°C/140°C) showed that it was possible to completely fill the cavities applying a higher mould temperature of 125°C and a low injection pressure of 800 bar."*

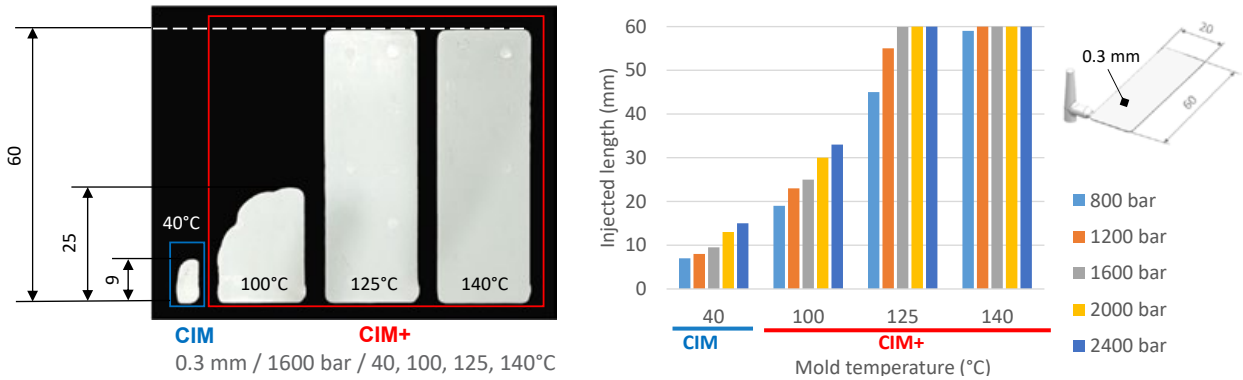

Fig. 8 Filling study of the 0.3 mm plate, with a zirconia feedstock with standard and variotherm injection conditions (mould temperatures at 40°C/100°C/125°C and 140°C, Melt temperature: 190°C) (Courtesy iRAP Institute, HEIA-FR/ HES-SO)

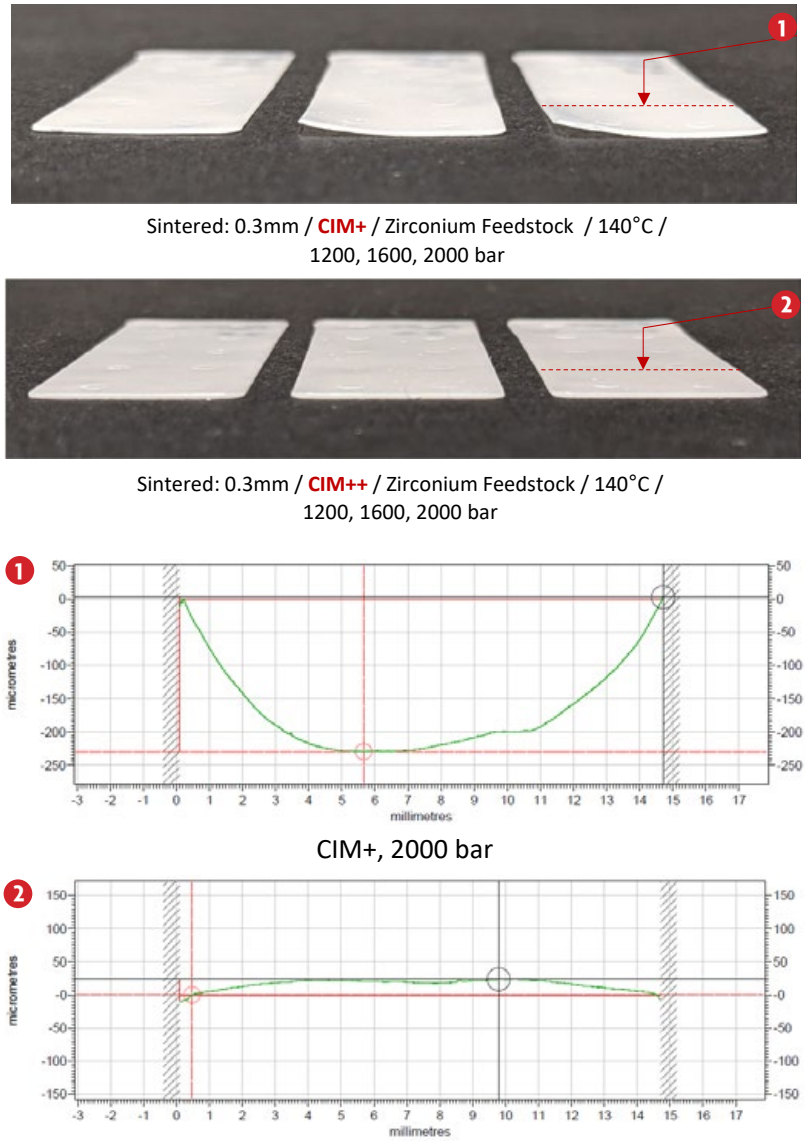

Fig. 9 Impact of variotherm and conformal cooling (CIM++) on the quality of the test plates with 0.3 mm thickness (Courtesy iRAP Institute, HEIA-FR/ HES-SO)

Filling study: plate with 0.3 mm wall thickness

The filling study based on thinner plates with a wall thickness of 0.3 mm (dimensions: 0.3 x 20 x 60 mm, sintered) demonstrated that, when using the standard CIM process, a flow distance of only 9 mm could be achieved (Fig. 8). With the application of variotherm (CIM+) technology, a significant increase in flow length was achieved. Applying 140°C and 800 bar, the cavity did not fill completely, however, 140°C and 1,200 bar enabled a complete fill. Complete fill of the plates was also achieved at 120°C and 1,600 bar.

Variotherm technology allowed for increased flow lengths so that the mould cavities could successfully be filled while maintaining relatively low injection pressures (800 bar for 0.5 mm and 1,200 bar for 0.3 mm). However, some residual part deformation was encountered after the sintering process (Fig. 9). Applying only variotherm (CIM+), the plates showed deformation that worsened with an increase in injection pressure. This part problem was successfully eliminated when applying a combined variotherm and conformal cooling (CIM++), resulting in flat plates after sintering. Deformation when using CIM+ was approx. 230 µm, and with CIM++ approx. 20 µm.

A Moldflow simulation was conducted to study the impact of

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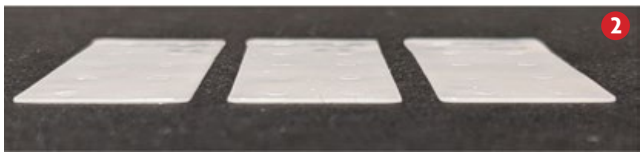
Sintered: 0.3mm / CIM+ / Zirconium Feedstock / 140°C / 1200, 1600, 2000 bar



Sintered: 0.3mm / CIM++ / Zirconium Feedstock / 140°C / 1200, 1600, 2000 bar

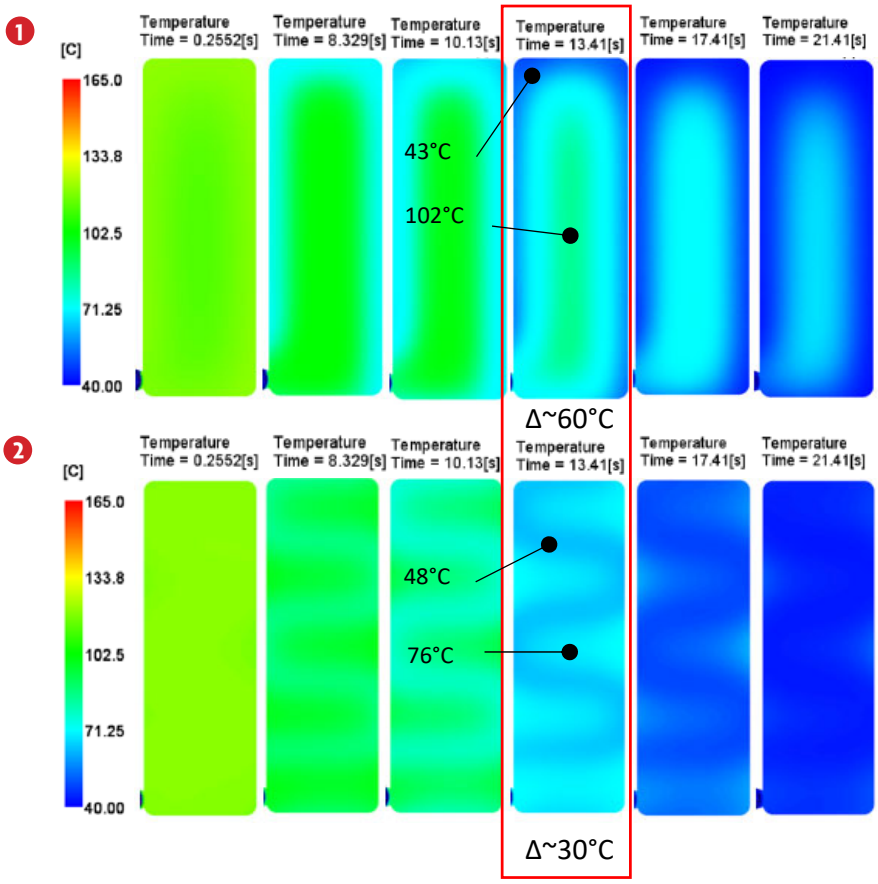


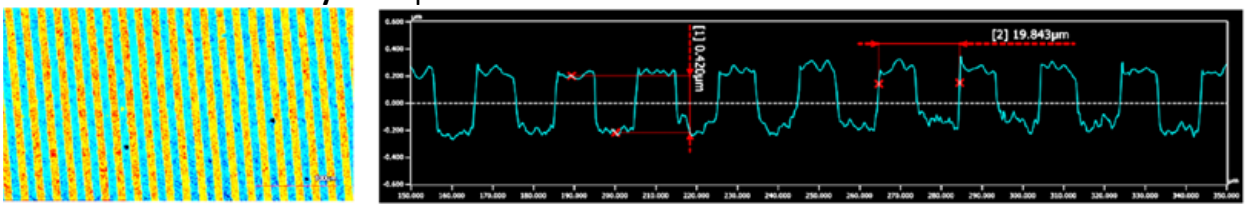
Fig. 10 Impact of variotherm and conformal cooling (CIM++) on the quality of the test plates with 0.3 mm thickness (top). Analysis and comparison of the mould cavity temperatures at the moment of the injection phase, for a variotherm (middle) and a combined variotherm and conformal cooling mould system (lower) (Courtesy iRAP Institute, HEIA-FR/ HES-SO)

the variotherm heating of the mould cavity before filling, compared to a combined variotherm and conformal heating. At t=13 seconds, inhomogeneous temperature of the mould cavity was noted with differences up to 60°C for pure variotherm that were reduced to 30°C when using the combined variotherm and conformal cooling (Fig. 10).

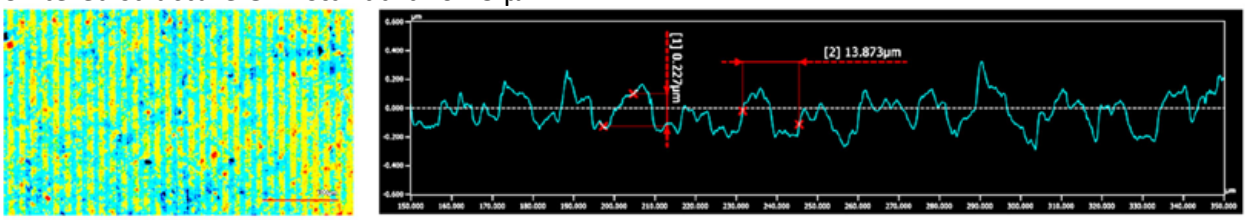
This mould temperature inhomogeneity is critical and creates internal stresses leading to greater deformation. With conformal cooling, a significant advantage was observed

"Applying only variotherm (CIM+), the plates showed deformation that worsened with an increase in injection pressure. This part problem was successfully eliminated when applying a combined variotherm and conformal cooling (CIM++), resulting in flat plates after sintering."

Structure in **mould cavity:** 0.42 µm



Sintered structure **CIM standard:** 0.23 µm



Sintered structure **CIM+:** 0.28 µm

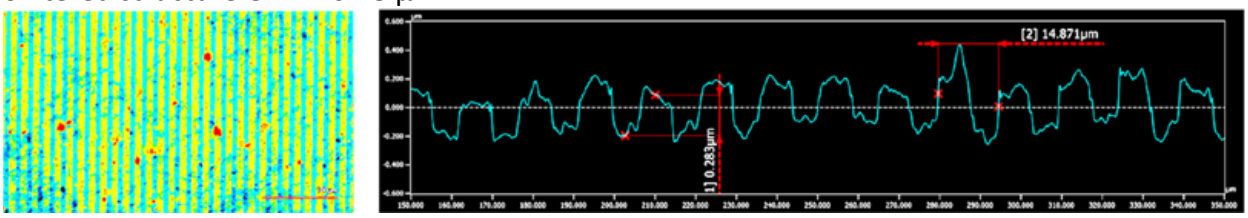


Fig. 11 Quality of the replication of a holographic structure with standard (CIM) and compared with variotherm (CIM+) (Courtesy iRAP Institute, HEIA-FR/HES-SO, Morphotonix [5]). Measured mean height of the structure in the mould cavity: 0.42 µm. Expected mean height of the structure on injected ceramic parts after debinding/sintering: 0.32 µm. Measured mean height of the structure realised with CIM standard: 0.23 µm. Measured mean height of the structure realised with CIM and variotherm (CIM+): 0.28 µm

with a more uniform mould temperature. These conditions are optimal for a more homogeneous cooling of the injected feedstock, a reduction of internal stress and, therefore, less warpage.

Potential for replication of fine structures

The application of variotherm technology is also enabling the successful replication of submicron surface details, such as holograms, through the Ceramic Injection Moulding process. The dimensions of the replicated structures corresponded approximately to the dimensions of the original mould texture when the feedstock shrinkage ratio was considered (Fig. 11). This high-quality replication is impossible with a standard CIM process. These tests have shown the significant potential of variotherm technology to integrate functional or decorative structures on CIM parts.

"The application of variotherm technology also enables the successful replication of submicron surface structures, such as holograms, through the Ceramic Injection Moulding process."

Conclusions

The exploration of innovative technologies such as variotherm and conformal cooling in Ceramic Injection Moulding through the CIM++ project has demonstrated the significant potential of these

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technologies for overcoming the limitations associated with the standard CIM process. The challenges faced in producing components with very thin walls, replicating fine surface details, and addressing quality issues such as cracking, deformation, and optical defects, have been effectively addressed.

Variotherm technology, widely used in plastic injection moulding, has shown promising results for the CIM process by introducing additional heating and cooling steps to the mould cavity. This has highlighted several advantages, including increased fluidity of the ceramic material, lower injection pressure, higher flow lengths and the ability to produce parts with very thin wall thickness in the range of a few tenths of a millimetre. Previous technical feasibility limits for thin-walled ceramic components can now be extended. Despite longer cycle times and increased mould design complexity, the benefits in terms of improved part quality, reduced internal stress, and better shrinkage control highlight the potential of the variotherm process for CIM.

Furthermore, the integration of conformal cooling systems, which involve the use of thermal circuits to achieve uniform mould cavity temperatures, has driven remarkable improvements in part quality. Conformal cooling imparts a uniform mould cavity temperature for complex geometries with fewer hot spots, faster cooling and a reduction of the total cycle time. Despite the associated time-consuming design phases and higher mould fabrication costs, the advantages of conformal cooling in terms of improved part quality, reduced internal stresses, and fewer moulding defects make it a valuable addition to the CIM process.

Fig. 12 A comparison of the quality of the replication of a holographic structure with standard CIM and variotherm (CIM+) (Courtesy iRAP Institute, HEIA-FR/HES-SO, Morphotonix [5])

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Acknowledgements

The authors would like to thank Innosuisse (Swiss Agency for Innovation), for its financial support of the research project CIM++ (57563.1 IP-ENG).

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The Additive Manufacturing of multi-material and multi-functional ceramic components

Additive Manufacturing's high geometric flexibility, when combined with the optimised properties of multi-material components, opens up new possibilities for designers and manufacturers. Recently, innovations in the design of the interfaces between different materials presents further opportunities with regard to the functionalisation and miniaturisation of components. In this article, Uwe Scheithauer, Fraunhofer IKTS, and Robert Johne, AMAREA Technology GmbH, explore the potential in the area of ceramic-based components produced using Multi Material Jetting (MMJ) technology.

Two points essentially determine the behaviour of components: the material used and the geometric shape.

The material used

The physical and chemical properties of a component are defined by the material used. If a component consists of only one material, it has the same properties in all areas. As an important part of a component's design process, a suitable material is selected from one of the many material classes according to the requirements of the application scenario. Depending on whether the choice falls on polymers, metals, ceramics or glass, the physical and chemical properties of the component differ significantly.

Polymer materials, for example, are notable for their low density, ease of production and very good machinability. In contrast, the production of ceramic components is much more complex due to the longer process chain, including thermal processing. However, ceramic components are significantly more resistant to chemical, thermal or mechanical stress, even compared to metals.

In an increasingly complex world, more and more challenging application scenarios are emerging in which combinations of material properties are required that do not exist in a single material. The following list contains some combinations of properties for more complex applications:

- Electrically conductive & insulating
- Thermally conductive & insulating
- Hard & ductile
- Dense & porous
- Magnetic & non-magnetic
- Multi-coloured
- A combination of different property combinations

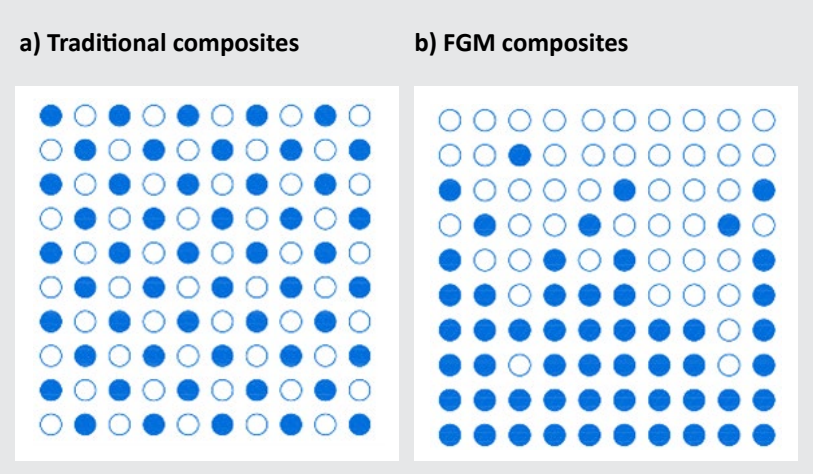

Fig. 1 Allocation of materials in a traditional composite (left) and a Functionally Graded Material (FGM) composite (right) [1]

Fig. 2 Left: ceramic glow plug (CIM) [2]. Right: pressure sensor, hybridisation of multilayer technology and CIM [3]

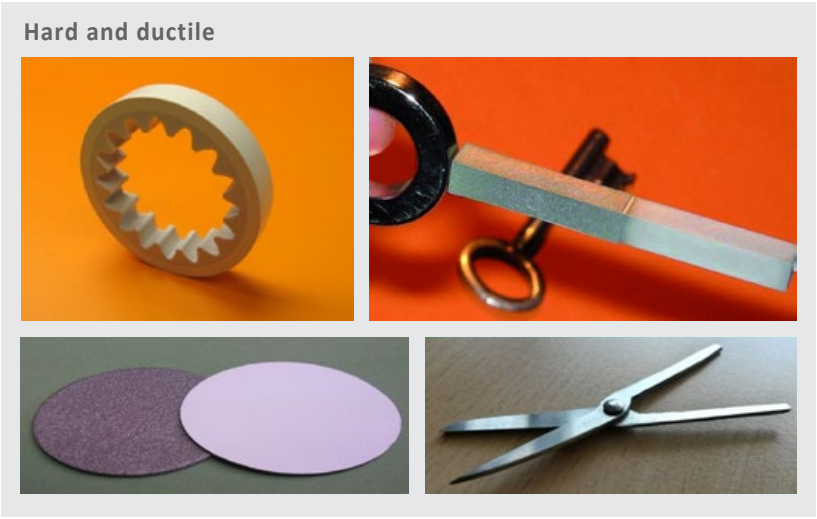

Fig. 3 Top left: alumina toughened zirconia (ATZ)/zirconia toughened alumina (ZTA) CIM components [4], top right: ZrO_2 and stainless steel via CIM [5], bottom left: ZrO_2 and stainless steel, multilayer [6], bottom right: cutting tools based on ZrO_2 and stainless steel, multilayer [7]

When single materials do not deliver the desired combination of properties, it becomes necessary to blend different materials in order to achieve the desired properties within a single component. Conventional composites, depicted in Fig. 1(a), consist of homogeneous mixtures. However, this often leads to compromises between the desirable properties of the individual component materials. In contrast, Functionally Graded Material (FGM) composites represent an even more advanced class of materials.

FGMs exhibit spatially varying material composition along a changing dimension (Fig. 1(b)), resulting in corresponding variations in material properties that are inherently built-in. By mapping strategies of allocating and structuring materials to the desired performance requirements, multifunctionality can be created in a component.

The following types of grading can be distinguished for FGMs:

Discontinuous grading
The component has discrete areas with different properties, wherein either material A or material B is present.

Gradient interface
There is a special intermediate layer between the two areas with different properties to create a smooth transition zone. Within this intermediate layer there is one mixture of materials A and B.

Gradual grading
The component has different discrete layers with different properties that are arranged in stages. Within a layer, the ratio between material B and material A is constant. As the number of layers increases, the difference in properties between the individual layers can be reduced.

Continuous grading
The component has a continuous variation of properties over the entire cross-section. The ratio between material B and material A increases or decreases continuously.

In some cases, it is not necessary to use two or more different materials. Instead, a single material can be employed in distinct states. For instance, it can serve as a dense structure in some areas and as a porous structure in others. This can be realised by varying the process parameters in Additive Manufacturing, for example, by varying the distance between the material deposits to generate areas with less, or no, material – and thus pores – in the subsequent component. Another example involves combining the same material but with different colours within a single component.

Component shape

Geometric functionalisation refers to the modification of the shape of a component in order to achieve certain functional properties. The shape, surface structure or microstructure of the material can be specifically modified in order to achieve specific properties (mechanical, optical, electrical, etc.). One example of geometric functionalisation is the use of surface structures, such as micro- or nanostructures, to improve the adhesion, friction or wettability of a material. Another possibility is to change the pore structure of a material in order to optimise its absorption or filtration properties.

Geometric functionalisation is used in various areas, such as lightweight construction (implementation of ribs

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and struts to increase rigidity and strength or the integration of cavities to reduce component mass), filtration technology or heat exchangers (increasing the exchange surface), biotechnology (targeted modification of wetting properties), toolmaking (integration of near-contour cooling channels) or gear technology (tooth profiles or gearing to optimise power transmission).

In the field of geometric functionalisation, the emergence of various technologies from the field of Additive Manufacturing has opened up a previously unrealised degree of freedom. As a result of the layered structure of the components during production, undercut, highly complex, or otherwise intricate geometries can be realised. These could not previously be achieved using methods such as casting, milling, drilling or eroding – or only at extreme expense. In addition, tool-free production via AM enables the flexible realisation of a wide variety of geometries in a very short time, so that iteration cycles can be significantly shortened.

Multi-coloured

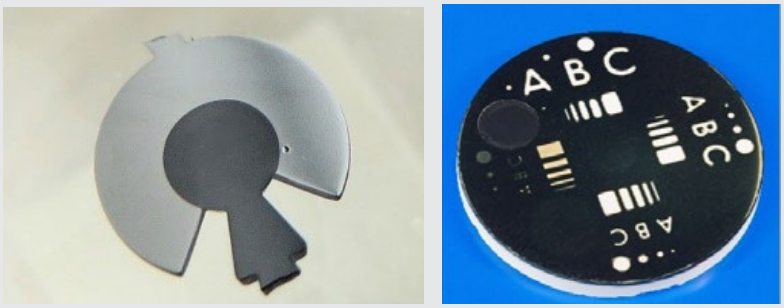

Fig. 4 Left: CIM hardmetal-cermet combination [10], right: jewellery components, In-mould-labeling (tape and CIM) [11]

Different porosities

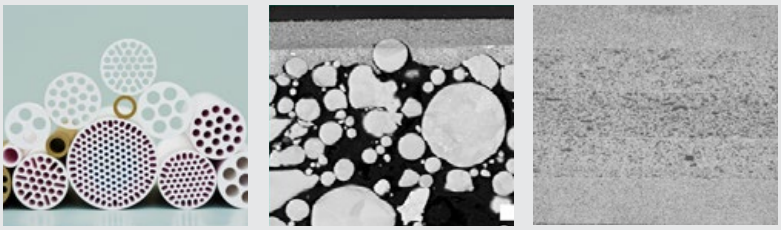

Fig. 5 Left: Filters, extrusion and coating, middle: filters based on ZrO_2 and stainless steel, multilayer/tape casting [8], right: refractories with multilayer graded porosity [9]

Additive Manufacturing of multi-material and multi-functional components

Current work is concerned with the development of processes and the associated device and process technology for the Additive Manufacturing of multi-material and multi-functional components. The combination of high geometric flexibility through Additive Manufacturing, and the optimised properties of multi-material components, opens up completely new possibilities for component designers and developers, not only in component design in general, but also in the design of interfaces between different materials. This results in disruptive innovations in a wide range of application areas, particularly with regard to the functionalisation and miniaturisation of components. From here, this article considers the potential in the area of ceramic-based components.

Special features of the ceramic process chain

Ceramic materials are used where other materials fail. They are characterised by outstanding thermal, chemical and mechanical properties, and also have a high lightweight engineering potential compared to many metals due to their relatively low density and high rigidity. Their good electrical insulation properties are also of interest for many applications, which is why ceramic materials are often used in high-voltage technology.

The challenges of the ceramic process chain result primarily from the final two-stage thermal processing. Firstly, all non-ceramic components of the feedstock that were necessary for shaping must be removed during debinding in order to enable complete densification and the formation of the expected ceramic properties during sintering. This also applies to additively manufactured ceramic components, as the various AM technologies used almost exclusively result in a green body.

As maximum temperatures of over 1500°C and shrinkage in the range of 50% by volume are not uncommon during sintering, there are two main challenges during the sintering of multi-material components. Firstly, only materials with similar coefficients of thermal expansion (CTE) can be processed together, as thermally induced stresses can lead to either deformities or deformation. This is due to a mismatch during cooling after sintering which can lead to failure in operation. In addition, the materials must have similar shrinkage behaviour, otherwise defects will be generated during sintering.

Figs. 2-5 show various examples in which ceramic-based multi-material components have been realised without AM technologies. Materials with comparable CTE were combined with each other and their shrinkage behaviour was adapted accordingly.

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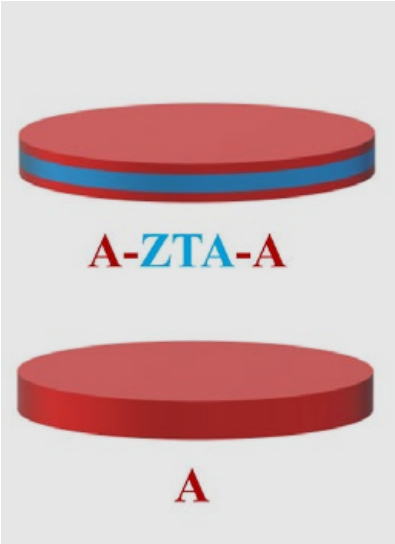

Fig. 6 Schematic of the multi-material approach by Schlacher et al. (top) compared to pure Al_2O_3 disks (below) [25]

CerAMfacturing = the AM of ceramics

The qualification of ceramic materials for various Additive Manufacturing technologies enables the production of parts with an unprecedented level of geometric complexity. For ceramic materials, which are extremely hard and also very difficult to machine due to their brittle fracture behaviour, AM technologies are game-changing manufacturing technologies. Highly complex geometries can be realised for the first time, or with significantly less effort, as post-processing is reduced or even completely eliminated. Additively manufactured ceramics are now a real alternative to components made of polymers and metals, especially for applications in harsh conditions.

The AM technologies used for ceramic materials are used almost exclusively as pure shaping technologies for the manufacturing of green bodies [12–14]. Consequently, all AM technologies known and used for polymers can also be used for the realisation of ceramic green bodies. The main difference is that the starting materials for the respective AM technology have a very high loading of ceramic particles. Typical values are in the range between 40 and 60% by volume.

With regard to the large number of different AM technologies, we refer here to the relevant standards [15], VDI guidelines [16,17] and review papers [12–14]. To avoid confusion with the AM of polymers, we at IKTS use the term CerAMfacturing (=AM of ceramics) and add the prefix CerAM to the various technologies.

Direct and indirect AM technologies

The various AM technologies can all be differentiated, for example, according to the type of starting material (e.g. granulate, suspension, filament) or consolidation (e.g. binder application, cross-linking, cooling). However, the type of material application is particularly important for the realisation of multi-material components. Zocca *et al.* [12] proposed a subdivision into direct and indirect AM technologies.

In indirect AM technologies, the starting material is applied over the entire surface of the installation space before selective consolidation of the starting material takes place, i.e. only in the areas that are required for the generation of the component in this layer. Typical examples are the AM technologies from the process classes Binder Jetting (BJT), Powder Bed Fusion (PBF) or Vat Photopolymerisation (VPP).

With direct AM technologies, the starting material is only deposited and consolidated where this is needed to create the current layer. This means that it is not necessary to remove the first unconsolidated starting material before another starting material can be deposited. Typical representatives are AM technologies from the Material Extrusion (MEX) and Material Jetting (MJT) process classes, in which different starting materials can be deposited directly next to each other using different dosing systems.

AM of multi-materials with indirect processes

Indirect AM technologies for ceramic materials offer large, scalable build spaces and high productivity (e.g. BJT, PBF) or very good component properties in terms of density, manufacturing tolerances and surface quality as well as maximum resolution (VPP). Commercial systems that have been specially developed for ceramic materials are mainly available in the VPP process class. The best-known suppliers are Lithoz (Austria), 3DCeram (France) and Admatec, now part of Nano Dimension (Netherlands). The portfolio of materials for these technologies is also growing and now includes not only Al_2O_3 and ZrO_2, but also Si_3N_4 and AlN and many more [18–23].

Scientific work on AM of multi-materials based on VPP has been published primarily for Lithoz's machine technology, which is commercialised under the name Lithography-based Ceramic Manufacturing (LCM) [24]. In the multi-material 2M30 machine, which was used for the following study, two different vats are used for the different starting materials, which can be moved alternately between the building platform (which can only be moved in the z-direction) and the stationary exposure unit. When changing between the vats or materials, a cleaning step is carried out to remove any non-crosslinked suspension still adhering to the component surfaces and to avoid cross-contamination between the vats.

The improvement of the mechanical properties was addressed in an article by Schlacher *et al.* [25]. The paper presents additively manufactured alumina disks with excellent biaxial strength using the 'layer-by-layer' capability of LCM technology. A multi-material approach enabled the combination of alumina-zirconia layers between pure alumina layers, which introduced significant residual compressive stresses into the latter as a result of the different CTEs during cooling after sintering (Fig. 6). A characteristic strength of more

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than 1 GPa was measured for the alumina multi-material system, compared to ~650 MPa for monolithic alumina, which serves as a reference.

Alumina samples exhibiting graded porosities are described in another article by Nohut *et al*. [26,27]. This was realised by combining two suspensions, to one of which a PMMA content of 20% was added as a sacrificial pore former. This made it possible to investigate the effects of the PMMA content on the resulting porosity, microstructure and mechanical properties. Fig. 7 shows an alumina component on a light source. This appearance results from the graded porosity and the refraction and scattering of light at the pores. [27]

Fig. 7 Alumina component with graded porosity [27]

AM of multi-materials with direct processes

Probably the best-known example of direct AM technologies is Fused Filament Fabrication (FFF), from the Material Extrusion (MEX) class of AM processes. Here, a thermoplastic filament is fed into a nozzle, melted, and applied. Solidification takes place purely via cooling, so that there are virtually no limitations in terms of the powders that can be processed. Different materials can be combined in one component using different nozzles, each of which processes a different filament.

In the field of ceramic materials, this has already been realised for combinations of electrically conductive and electrically insulating material mixtures based on Si_3N_4 and $MoSi_2$. Fig. 8 shows a component for a heater application during a functional test. The two different mixtures are matched in such a way that comparable shrinkage properties and thermal expansion coefficients are achieved. This work was a collaboration between PolyMerge, Tiwari Scientific Instruments and Fraunhofer IKTS [28]. An almost identical material pairing was also qualified for Multi Material Jetting (MMJ), an AM technology from the MJT class, and is described in detail below.

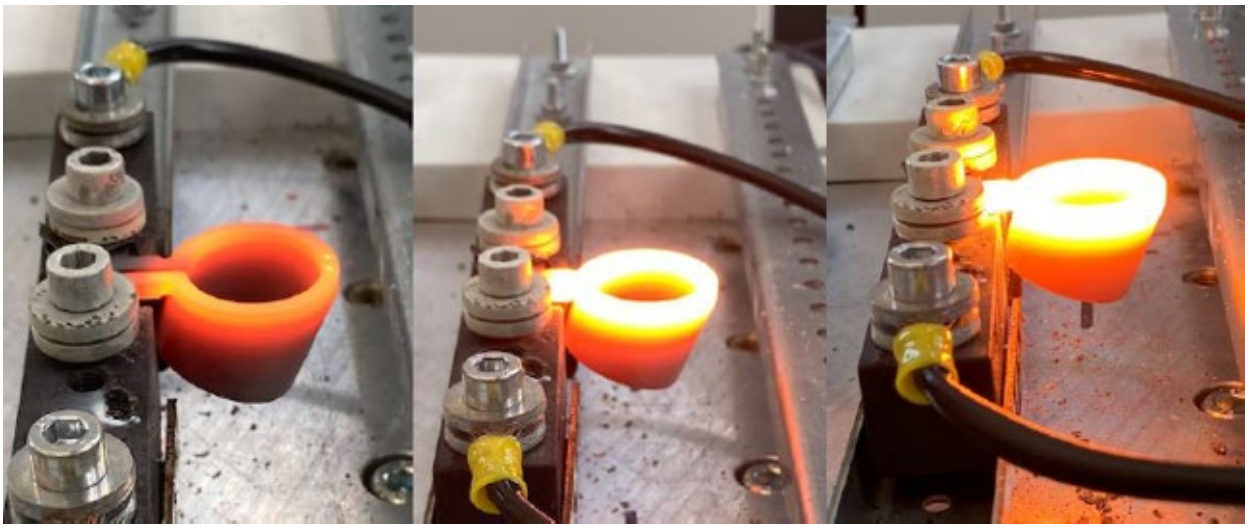

Fig. 8 CerAM FFF component for heater applications based on two mixtures of Si_3N_4 and $MoSi_2$ resulting in an electrically conductive-insulating-combination in the sintered state

Fig. 9 From left: Robert Johne, Steven Weingarten and Lutz Gollmer, as well as Philipp Horn (not in frame) commercialise the in-house developed Multi Material Jetting (MMJ) technology at the Fraunhofer IKTS spin-off AMAREA Technology GmbH (Courtesy AMAREA Technology GmbH)

Multi Material Jetting (MMJ)

Multi Material Jetting (MMJ) occupies a unique position in the AM landscape with its capability for multi-material Additive Manufacturing (MMAM). Positioned between Fused Filament Fabrication (FFF) and stereolithography-based VPP, MMJ bridges the gap by combining favourable feedstock properties with an innovative shaping logic.

MMJ was first developed in 2014 at Fraunhofer IKTS Dresden. Since then, a wealth of knowledge and experience has been gained and demonstrated with more than fifteen materials and material combinations qualified for use on MMJ-based multi-material AM machines. These in-house-developed AM machines produced convincing prototype components, serving a diverse range of industrial customers, but the journey of MMJ did not end there.

As part of the Fraunhofer-Gesellschaft's commitment to applied research and translating technological breakthroughs into tangible benefits for the economy and society, researchers from Fraunhofer IKTS (Fig. 9), supported by the German Federal Ministry for Economic Affairs and Climate Protection (BMWK) through the EXIST research transfer funding programme, founded AMAREA Technology GmbH in February 2023 [29]. The Dresden-based company's mission is to commercialise MMJ by transitioning the cutting-edge AM machines and materials into series production for use in industrial manufacturing [30].

In MMJ, the feedstocks are low-viscosity thermoplastic suspensions that contain the material as a powder – a different feedstock contains a different material powder or powder mixture. Remarkably, MMJ feedstocks accommodate high solid-loading levels, ranging from at least 40% to beyond 50% volume, using a diverse array of ceramic powders, regardless of their material characteristics or optical properties [31–33]. This versatility extends from ceramics, such as, among others, black and white zirconia, alumina, and silicon nitride to glass, metals, hardmetals and cermets [32–35] [MMJ02-05]. Technically, almost any powder can be used in a MMJ feedstock, depending on the powder properties and the specific desired material properties – one of the two features, making MMJ capable of MMAM.

MMJ's second important feature for MMAM lies in its unique shaping logic. In MMJ, a feedstock is selectively deposited as single droplets using a piezoelectric micro dispensing system. These tiny droplets precisely fuse together in the x-y direction, forming filament-like structures (Fig. 10), which can then be fused to form flat structures.

Ultimately in the z-direction, the process of stacking and fusing together results in the creation of intricate 3D objects. The small dimensions of these nanolitre-sized droplets allow for exceptional resolution in the range of a few hundred micrometres. Altering the micro dispensing parameters enables a controlled flexibility in droplet resolution. The deposition rate can be increased up to 800 droplets a second.

Multiple micro dispensing systems, each loaded with a distinct feedstock containing a different powder composition, allow diverse materials to be deposited next to and on top of one another building a

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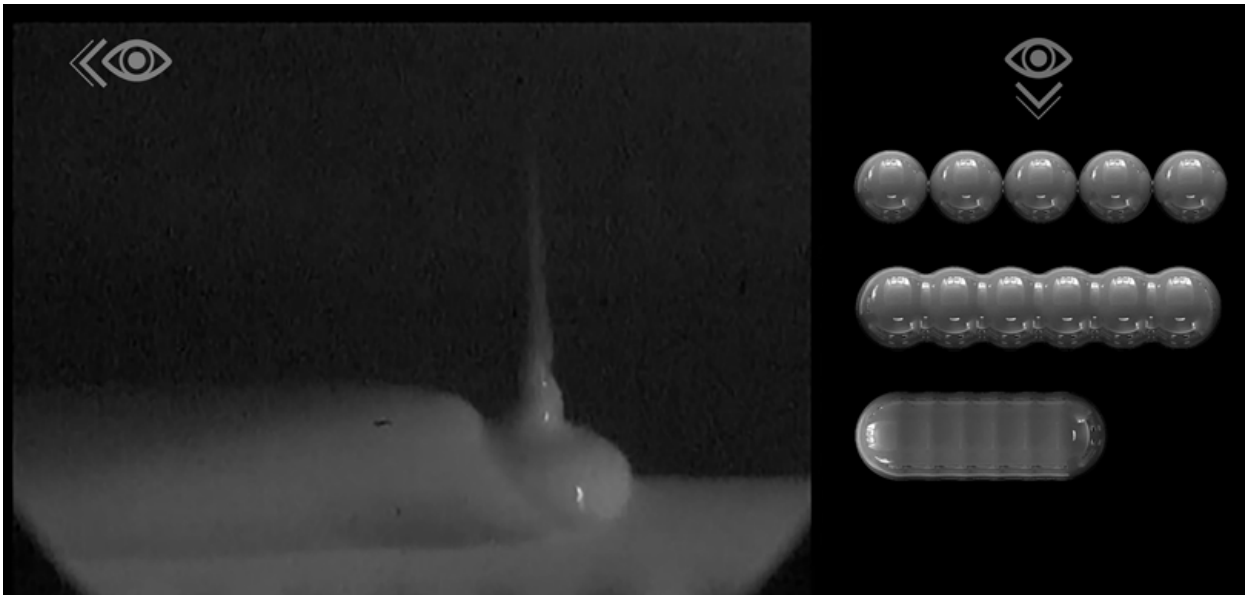

Fig. 10 Single video frame of high-speed recording of MMJ: a subsequent drop is deposited and fuses with a preceding drop (left). Top view of overlapping drop deposition process (right)

multi-functional component during a single build job. Sagging and collapse of large overhangs are prevented by adding support material as a temporary element during the shaping. The overall spatial control of MMJ enables not only MMAM, but also functionally graded AM.

A preview of AMAREA Technology's multi-material AM machine

To further expand the possibilities of multi-material and functionally graded AM, the MMJ-based system technology is being constantly evolved.

Starting from the three print heads (micro dispensing systems) in Fraunhofer IKTS's demonstration machine, i.e. up to three different materials that can be used in an additive build job, the number of print heads and thus co-3D-printable materials has already been increased up to six, as AMAREA Technology shows in the preview of its first series industrial multi-material AM machine.

The MMJ Pro System is a modular and upgradable industrial AM machine with tailored control software (Fig. 11). In addition to the (up to six) print heads, a 3D profile sensor for automated in-line monitoring, build job documentation, and accelerated parameterisation is included as standard. The system is designed to also work with particularly hard materials, such as those typically used for technical ceramic applications. Because of their hardness, the machining of sintered components is very costly. For this reason, an optional laser module will be offered for the system in the future. The laser will not only enable the smoothing of outer surfaces to a surface roughness as low as, or even below, 1 µm Ra, as demonstrated during test runs in the past, but, in the future, also enable the targeted ablation and defined in-line structuring of the individual layers of the green body for a hybridised additive-subtractive processing during shaping. This will not only further improve manufacturing tolerances,

Fig. 11 Preview of AMAREA Technology's series industrial multi-material AM machine based on MMJ with six print heads (left to right), integrated 3D profile sensor (right), and optional laser module (centre)

Up to six print heads:	Combine up to six different materials drop-by-drop and layer by layer at high-precision throughout the build volume
Integrated 3D profile sensor:	For automated in-line monitoring, build job documentation, and accelerated parameterisation
Optional laser module:	For in-line green processing, such as ablation, structuring, and smoothing
Building envelope (x | y | z):	up to 530 mm x 300 mm x 200 mm
Lateral resolution (xy):	from 200 µm for build material
	from 100 µm for support material
Layer thickness (z):	from 100 µm for build material
	from 100 µm for support material
Design file format:	i.e., .3mf (native, open source)

Table 1 Technical properties of the modular MMJ Pro System

Oxide, nitride and carbide ceramics	Alumina
	Zirconia
	Aluminum nitride
	Silicon nitride
	Silicon carbide
	Silicon carbide – Glass
	Titanium oxide
Hardmetals and cermets	Tungsten carbide cobalt
	Titanium carbonitride
Sintered glasses	Borosilicate glass
Metals and precious metals	316L
	17-4PH
	Silver
Glass-ceramics	LTCC
Polymers	Particle-filled thermoplastics
	Polycaprolacton

Table 2 Materials which have been processed with MMJ

"The ability to utilise virtually any powder for MMJ feedstock production enables Fraunhofer IKTS and AMAREA Technology to rapidly expand their portfolio beyond its current state."

but also ensure the customised design of the interface between different materials. Table 1 summarises the technical properties of AMAREA Technology's modular MMJ Pro System.

Materials for MMJ

Over almost a decade of material development, the range of materials used with the MMJ technology has grown steadily. The wide range of materials is summarised in Table 2. The ability to utilise virtually any powder for MMJ feedstock production enables Fraunhofer IKTS and AMAREA Technology to rapidly expand their portfolio beyond its current state. Interested companies can provide the powder, and with the assistance of Fraunhofer IKTS and AMAREA Technology, have a customised feedstock tailored to their specific needs. AMAREA Technology refers to this service as Bring Your Own Powder, or BYOP. Additionally, if the appropriate materials have not yet been identified, the partners can assist in identifying and sourcing them for customisation.

MMJ case study: Temperable tool for forming applications

While the technical details of MMAM and the MMJ technology may not immediately reveal the full extent of its benefits beyond component functionality and performance, a specific real-world example – along with the associated requirements and the solution through MMJ – can illuminate its overall advantages.

For that purpose, an application is envisioned where a 'temperable' tool for a forming solution is needed. It is rather a common theme in real-world forming processes where something needs to be formed to have heating or cooling involved as part of the process and to adapt the temperature as a means of process control. The requirements of such a tool

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are summarised in Fig. 12, which depicts a mock-up design sketch for such a temperable tool's requirements. The component's multi-material design, including shape and materials, is shown in Fig. 13. Fig. 14 shows an example component actually manufactured by MMJ including consecutive debinding and sintering during testing of the heating function. This component demonstrates how well the additively manufactured multi-material design meets the following requirements:

A single, durable and complex component

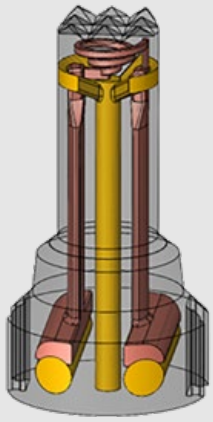
The textured tip, shaft, and flange come as a single durable component including fine details such as surface texture or the contour of the flange (design features (A) - (D), meeting requirements (1) - (7)).

Integrated heating function

A heating function is solid-state integrated by a heating coil in the immediate vicinity of the textured tip and easily accessible connection points in the flange, both of which are connected to each other via insulated electrically conductive pathways running through the shaft (design features (D) - (G) meeting requirement (8)).

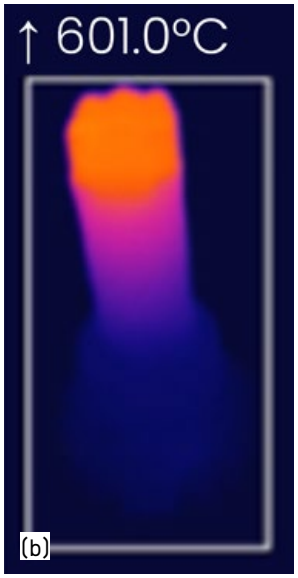
- (1) A texturised tip as a mold,
- (2) topping a shaft to reach the blank,
- (3) which ends in a wider flange by which the tool itself can be attached to a spatial manipulator.
- (4) The base material should be strong,
- (5) hard,
- (6) chemically inert,
- (7) and with minimal thermal expansion and hence being dimensionally stable and durable.
- (8) A heating function
- (9) and a cooling function need to be integrated in the component for temperature control.

Fig. 12 Sketch of the temperable tool and its requirements



- (A) Integrated defined textured tip.
- (B) Integrated shaft extending the textured tip.
- (C) Integrated wider flange extending from the shaft.
- (D) Strong, hard, chemically inert, and low CTE silicon nitride (Si_3N_4) with low contents of molybdenum disilicide ($MoSi_2$) as base material with an electrical insulating behavior.
- (E) Integrated heating coil right below the textured tip made of electrically conductive Si_3N_4-$MoSi_2$ (due to higher contents of $MoSi_2$). The resistance is set by the design of the coil.
- (F) Integrated electrical pathways made of electrically conductive Si_3N_4-$MoSi_2$ run from the heating coil, inside the shaft down to connection ports in the flange.
- (G) Integrated connection ports in the flange.
- (H) Integrated ventilation ducts close to textured tip and heating coil.
- (I) Integrated ventilation channel to supply the ducts with coolant from the insertion side at the flange.

Fig. 13 Multi-material design draft for the temperable tool



(A), (B), (C), (D) [Fig13]	(1), (2), (3), (4), (5), (6), (7) [Fig12]	Textured tip, shaft, and flange come as single durable component including the fine details such as the texture of the tip or the contour of the flange.
(D), (E), (F), (G) [Fig13]	(8) [Fig12]	A heating function is solid-state integrated by a heating coil near the male part and easily accessible connection points in the flange, connected to each other by electrically conductive pathways running isolated through the shaft.
(H), (I) [Fig13]	(9) [Fig12]	A cooling function is integrated as part of the structure by ventilation ducts close to the and heating coil and a channel running from the ducts through the shaft to an accessible coolant insertion side at the flange.

Fig. 14 (a) component during testing of the heating function (photo of the test), (b) single video frame of the thermal imaging showcasing a temperature of of about 600°C (overall capable of close to 1500°C)

Integrated cooling function
A cooling function is integrated as part of the structure through ventilation ducts near the textured tip and the heating coil as well as a channel running from the ducts through the shaft to an accessible coolant inlet side on the flange. (design features (H), (I) meeting requirement (9)).

Other less obvious user benefits for the temperable tool case study are as follows:

A fast, efficient, safe and strong design
The heating coil is spiral-shaped and positioned close to the textured tip. Its design ensures fast, efficient, and safe heating. As it is a solid-state integrated heating coil, it minimises the risk of degradation and fire hazards associated with its function. Additionally, the coil heats locally where needed, and the specific geometry acts as a semi-decoupling mechanism to other areas of the component. This minimises heat transfer to the rest of the component including all attachments, e.g. when the component is attached to a spatial manipulator on the flange.

Integrated conductive pathways
The integrated conductive pathways are designed to run inside the shaft as a solid-state conductor. This configuration ensures both safety and reliability. By incorporating the conductive pathways directly into the shaft, the risk of fire hazards is minimised, and damage or degradation of the conductive and insulation performance is prevented, especially when compared to traditional cable wiring methods.

Integrated electrical connection
Integrated electrical connection points are designed with connectors as part of the flange. This configuration ensures easy accessibility to connection points for power supply. By incorporating the connectors directly into the flange, users can conveniently establish electrical connections without the need for additional components or complex wiring.

Integrated ventilation
Integrated ventilation ducts and a supply channel are strategically positioned close to the textured tip and heating coil, with the channel running inside the shaft. This design ensures efficient, reliable, and easily accessible cooling. The cooling is localised to where it is needed, minimising heat transfer to the mounting (effectively creating an 'air-conditioned' shaft) and providing shielding for other areas of the component. Additionally, an easily accessible interface is provided for coolant supply.

Conclusions

The case study only uses multiple materials in a single, dense state. Considerable unexplored opportunities exist to employing materials in distinct states. For instance, in addition to dense areas, porous structures could serve to provide additional heat shielding in other areas. MMAM opens up completely new freedoms in component design, and MMJ technology is one of the pioneers here. The following is a summary of the overall benefits using MMJ:

A multitude of diverse functions
A multitude of diverse functions stemming from contrasting material properties, such as electrically conductive and non-conductive behaviour, among others, can be integrated into a single component. This can lead to the production of innovative components that were previously impossible to produce with only a single material.

The functionalities of an assembly without a need to assemble
Multi-material components are not only realisable but also provide the functionalities of an assembly without the actual need to assemble – eliminating the need for complex, time-consuming, and design restricting joining methods. MMJ can, therefore, reduce complex production pipelines for assemblies through the MMAM of an assembly as a single component in a single build job.

MMAM integrates functions without the need for assembly or joining and pairs it with the capability of scaling dimensions. This leads to the integration of more functions, often requiring a miniaturisation approach, which MMJ delivers as a single build job. Furthermore, with the ability to design and scale interfaces according to a component's added functionality and its application environment, using MMJ enables the production of the specific connection interfaces.

"The challenge and opportunity now is to think in a completely new way. For the different application scenarios, the required functionalities and the real existing boundary conditions (not the limitations that exist in people's minds) must be identified and compared with the possibilities of the materials and production technologies."

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Design iterations

Adapting the design and going through design iterations for MMAM is primarily a digital process. 'Design for MMJ' speeds up the engineering, prototyping, and testing phases and saves resources along the way.

The possibility to not only adapt the design in terms of shape, but also the materials, enables other material combinations to be used if it becomes necessary or is advantageous in future product interactions. Hence, when an operating environment changes, far more than just shape requirements can change. MMJ can provide solutions with other material combinations.

Fig. 15 shows further MMAM components based on ceramic materials and the corresponding literature references. This is just a small selection, without any claim to completeness, which represents the beginning of a fantastic journey.

The challenge and opportunity now is to think in a completely new way. For the different application scenarios, the required functionalities and the real existing boundary conditions (not the limitations that exist in people's minds) must be identified and compared with the possibilities of the materials and production technologies. And even if it may not yet be possible to realise the required component, it is important to always remember how quickly the world is changing and technologies are developing.

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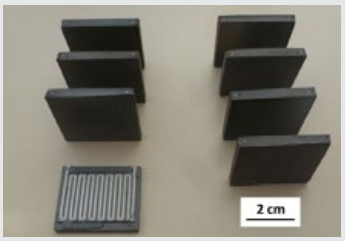
Electrically conductive and insulating

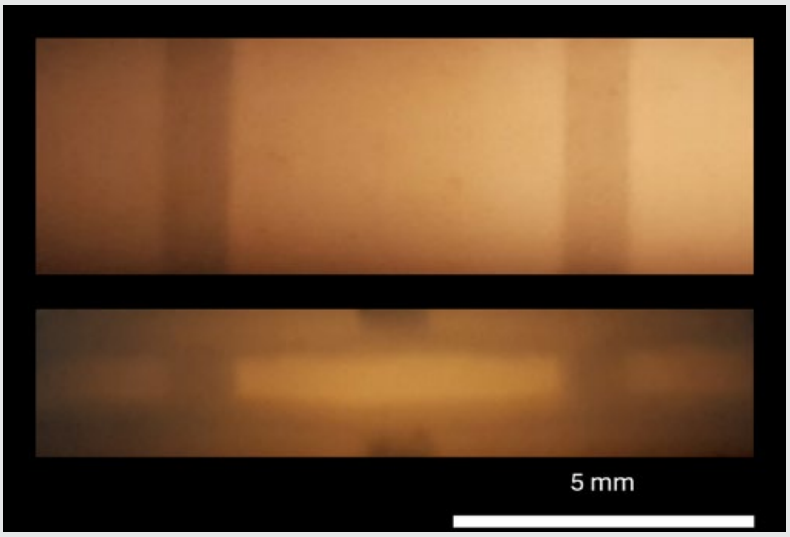
Ceramic igniter based on Si_3N_4-$MoSi_2$-mixtures, CerAM MMJ [36,37]

Ceramic heater based on Si_3N_4-$MoSi_2$-mixtures, CerAM FFF [28]



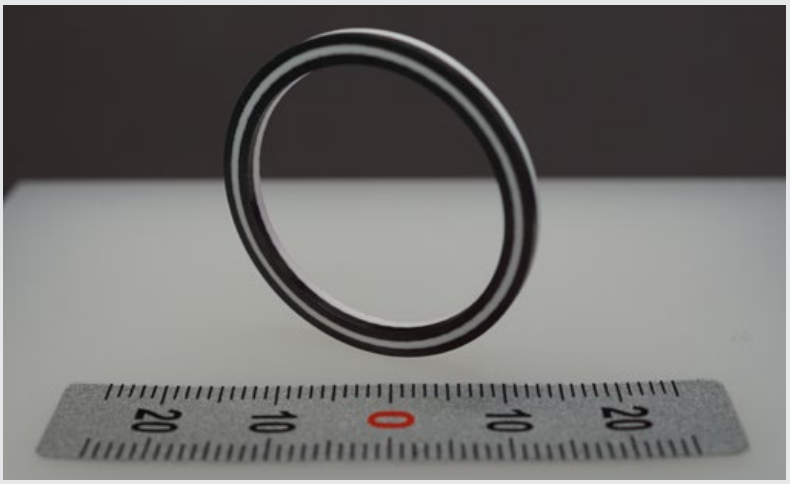
Ceramic heater based on stainless steel and zirconia, CerAM FFF [38]

Dense and porous



Dense and porous zirconia component, CerAM MMJ

Multicoloured



Ceramic ring based on white and black zirconia, CerAM MMJ [31]

Fig. 15 Further examples for ceramic-based additively manufactured multi-material components

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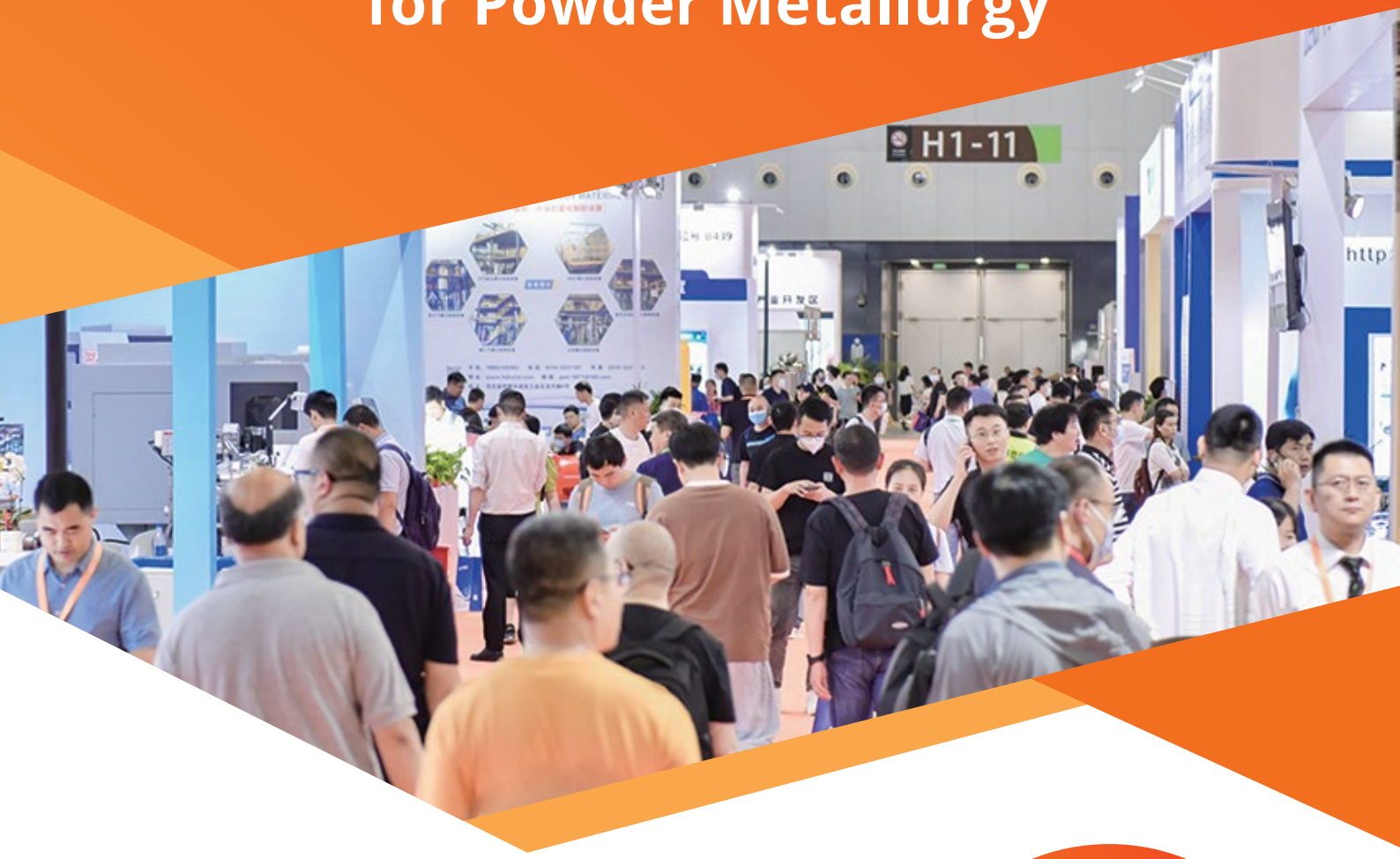

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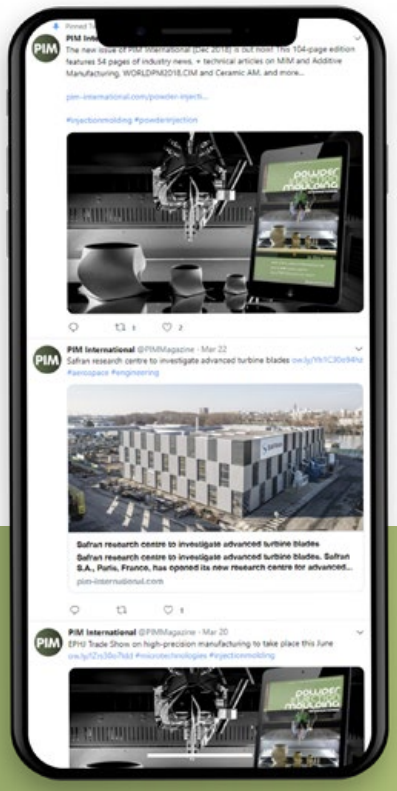

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