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FOR THE MIM, CIM AND SINTER-BASED AM INDUSTRIES

powder injection moulding INTERNATIONAL

in this issue

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POWDER INJECTION MOULDING INTERNATIONAL

For the MIM, CIM and sinter-based AM industries

Awards: The greatest resource for promoting MIM technology?

"The best manufacturing process for small, precision components that you've never heard of." It's a phrase that I find myself turning to all too often in conversations about what I do. Whilst day in, day out, we all play a role in trying to spread the word about MIM, in this issue of *PIM International* we decided to 'wave the flag' for the technology that bit harder by celebrating the MIM award winners in the MPIF's 2022 PM Design Excellence Award Competition in our lead article.

International component award competitions have been organised by regional trade associations across the wider PM world for many years, but we never see so many examples of MIM parts outside of the MPIF's competition. Because of this, it's impossible to overstate just how important this competition has become to shining a spotlight on MIM.

Of course, considerable effort lies behind such a competition. Companies not only have to persuade their customers to allow a part to be submitted, but prepare detailed entries, and associations then have to manage the competition process, whilst a committee of volunteers with the necessary expertise sifts through the many entries to select the winners.

Our role? Spreading the word, not only about MIM but sinter-based AM processes, to the international community. Digital marketing, combined with on line publishing, is allowing us to reach carefully targeted audiences that would never have been possible a decade ago.

Nick Williams,
Managing Director & Editor

Cover image
A 316L stainless steel rotary wheel used in an automotive interior, manufactured by Kyerim Metal Co., Ltd for Hyundai (Courtesy MPIF)

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September 2022

Powder Injection Moulding International

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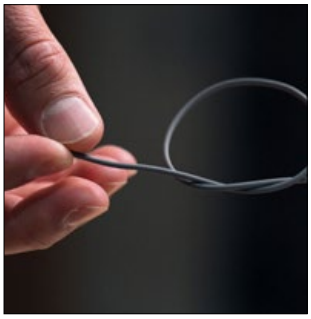

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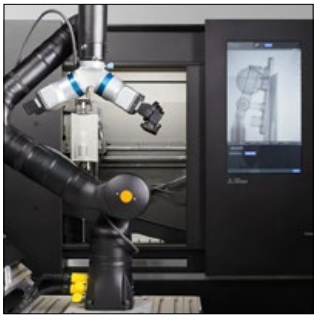

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Meet us at FORMNEXT, Hall 12.0 - Booth C127, 15-18 Nov. 2022

Digital Metal® – a Markforged Group company

Regular features...

Industry News

Alliance MIM additively manufactures stainless steel watch case for luxury watchmaker

Alliance MIM, Saint-Vit, France, has partnered with French watchmaker Carzo & Lieutier to additively manufacture a 316L stainless steel bezel dial case for the limited edition Héroïne watch.

Sixteen Héroïne watches were manufactured using a hybrid process that combines binder jet Additive Manufacturing and CNC machining. The watches, each costing €1,980, are reported to have sold out.

Alliance MIM manufactures and sells technological solutions made from Binder Jetting and Metal and/or Ceramic Injection Moulding. The company focuses on the production of highly technical, small and high-value-added assemblies.

The company works with 316L, 17-4PH and PANACEA stainless steel; 42CrMO4, 420, FN08 steel for heat treatment; 8620 case hardening steel; Grade 4 titanium alloy; W3Ni tungsten; white & black zirconia ceramics; and Hastelloy X, Inconel 718 and RENE77 superalloys.

www.alliance-mim.com

Alliance MIM produced the bezel dial case of Carzo & Lieutier's Héroïne watch (Courtesy Carzo & Lieutier)

Key automotive MIM order a boost to Oechsler Group

The Oechsler Group, headquartered in Ansbach, Germany, has announced its results for the financial year 2021, seeing a significant impact from the COVID-19 pandemic and rising raw material prices. Group sales decreased by 2.4% to €369 million (2020: €378 million). Despite this, the group states that it is satisfied with its 2021 results, having made further progress in expanding Additive Manufacturing as a production technology alongside its polymer, metal and ceramic injection moulding. Growth was also provided by a key order from a leading automotive supplier for the series production of components made using Metal Injection Moulding.

The group operates Automotive, Sporting Goods and Innovative Solutions divisions at three German and seven production sites globally. In the past year, its Automotive segment saw a sales increase of 10% to €257 million. Under this segment, Oechsler primarily produces electronic parking brakes (EPB) and assistance systems for autonomous driving. The group states that it is expanding its material portfolio beyond polymers and ceramics in order to implement MIM.

In 2020, the group expanded its portfolio in toolmaking and can now additively manufacture metal tool elements. The group has extensive polymer AM capabilities and emphasised the importance of Additive Manufacturing within the Oechsler Group, which has been steadily increasing in recent years. The share of the product portfolio in group sales continues to be over 10%.

For 2022, Oechsler is planning total investments of around €55 million, of which the company has already invested €20 million in the first quarter. The group plans to continue its investment in its Additive Manufacturing offering as well as its projects to reduce CO_2 emissions. Oechsler sees relevant growth opportunities in the healthcare market in the future.

"The level of CO_2 emissions has become a key performance indicator for Oechsler. The emissions per manufactured component play an increasingly decisive role in the competition for large orders. In addition to our social responsibility, the reduction of greenhouse gases is thus becoming increasingly important for Oechsler's business success," stated Dr Claudius M Kozlik, CEO of Oechsler AG. "As early as 2022, we expect group sales to rise again and see considerable growth opportunities in the medium term – especially due to promising new projects in 3D printing."

www.oechsler.com

HP launches modular Metal Jet S100 Solution for Binder Jetting

HP Inc., Palo Alto, California, USA, has announced that its Metal Jet S100 Solution for metal Binder Jetting (BJT), featuring multiple modules for the BJT workflow, including depowdering and curing, is now commercially available. The announcement was made during the 2022 International Manufacturing Technology Show (IMTS), where HP showcased its metal Additive Manufacturing technology.

Designed for the mass production of additively manufactured parts, the Metal Jet S100 Solution provides high-volume production capabilities and is available to purchase as part of an integrated workflow via a subscription and service offering, with the company claiming "an unprecedented level of technical and business advantages for customers, helping them achieve their goals for business transformation." The modular solution enables build units to be transferred between four different stations, meaning users can continually run production at scale for mass metal production.

These four 'stations' include the Metal Jet S100 Powder Management Station, HP Metal Jet S100 Printer, HP Metal Jet S100 Curing Station and the HP Metal Jet S100 Powder Removal Station. Notably, the powder removal station enables automated powder removal as an integrated step in the workflow, and can be tailored to the specific needs of different applications. Sintering equipment, for the final stage in the BJT workflow, is available from third-party providers.

"We are witnessing entire industries, from industrial to consumer, and healthcare to automotive, looking to digitally transform their manufacturing processes and supply chains in a world where volatility is the new normal," stated Didier Deltort, president of HP's Personalization and 3D Printing business. "As the promise of Additive Manufacturing takes hold, HP has become a trusted partner to help speed the path to production. The introduction of our new Metal Jet commercial solution, along with innovative collaboration with market leaders like Schneider Electric, is delivering the blueprint for more sustainable, reliable, and efficient manufacturing."

Ramon Pastor, Global Head and General Manager of 3D Metals, HP Inc, commented, "Since announcing the breakthrough Metal Jet technology in 2018, we have been working to develop the industry's most advanced commercial solution for 3D metals mass production. 3D printed metal parts are a key driving force behind digital transformation and the new Metal Jet S100 Solution provides a world-class metals offering for our customers, from the first designs right through to production, but more importantly, helps them to realise the unlimited potential for digital manufacturing."

Among recent Metal Jet success stories highlighted by HP at IMTS was recent customer Schneider Electric, which used the company's Metal Jet technology, along with production support from GKN, to produce a new filter that was used on Schneider Electric's NSX breaker. The filter could not have been manufactured using conventional methods due to the complexity of the final shape in the material selected. HP Metal Jet technology is reported to not only have facilitated the design of new power filter shapes that reduce gas, pressure, and heat impact in a more limited space, but also resulted in significant productivity gains and environmental benefits.

Michael Lotfy, SVP of Power Products & Systems, North America, Schneider Electric, added, "We are excited about the new possibilities for our business as a result of this collaboration with HP. We are constantly in pursuit of solutions that will enable more sustainable, agile innovations development. Leveraging HP Metal Jet our teams have delivered a proven use case showcasing the benefits of digital manufacturing and 3D printing, and we look forward to uncovering many more applications that meet the evolving demands from our customers addressing the challenges around sustainability and Electricity 4.0."

www.hp.com | www.se.com

HP's new Metal Jet S100 Solution for metal Binder Jetting, which features multiple modules including depowdering and curing, is now commercially available (Courtesy HP)

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Nippon Piston Ring and Riken Corporation plan merger to form NPR-Riken Corporation

Nippon Piston Ring Co., Ltd., Tokyo, Japan, and Riken Corporation, Tokyo, Japan, have announced a Memorandum of Understanding (MoU) to establish a joint holding company formed by mutual stock transfer, and to consolidate the two companies on equal terms. The MoU has been resolved by the board of directors of the two companies and the trading name of the new joint company will be NPR-Riken Corporation.

Founded in 1934, NPR is recognised for its high-performance, high-quality Powder Metallurgy piston rings, valve seat inserts, camshafts, and other parts primarily for use in internal combustion engines. In addition to press and sinter PM, the company also uses Metal Injection Moulding to manufacture a wide range of components.

Riken was established in 1927 to commercialise the research out of the Institute of Physical and Chemical Research and has contributed to the development of the global automotive industry for over ninety years through its study of surface treatment, processing and materials technologies for piston rings and other components.

The automotive industry is undergoing a remarkable transformation, and the market for internal combustion engine parts is becoming more restricted. To address this, while the internal combustion engine remains the primary form of powertrain, the companies are dedicated to developing components that enable more environmentally friendly engines. The companies also believe it is necessary to increase investment in new business areas that address global Sustainable Development Goals (SDGs) and Environment Social Governance (ESG), reducing carbon dioxide emissions and protecting the environment. Additionally, NPR and Riken will work to accelerate efforts in the fields of marine, hydrogen, new energy projects, thermal engineering, electromagnetic compatibility (EMC), medical equipment, axial motors, MIM and other non-automotive engine parts.

Through the formation of NPR-Riken Corporation, the two companies plan to integrate and utilise the management resources of both companies. It will enable the reduction of costs through shared use of infrastructure and other resources, further reducing manufacturing costs by improving production efficiency through shared product integration.

Once the formation of NPR-Riken Corporation is approved at each of the company's shareholder meetings, and subject to the necessary approval of relevant authorities, the two companies plan to engage in a joint share transfer in April 2023. It is reported that the president of Riken will assume the position of CEO of NPR-Riken Corporation and the president of NPR will assume the position of COO of NPR-Riken Corporation.

www.npr.co.jp
www.riken.co.jp

Nippon Piston Ring received a JPMA award iron based sintered component which is used in an aluminium engine block (Courtesy JPMA)

Bodycote expands Hot Isostatic Pressing capacity at its Greenville site

Thermal processing services provider Bodycote plc, headquartered in Macclesfield, Cheshire, UK, reports that it has expanded its Hot Isostatic Pressing (HIP) capability with two additional vessels at its site in Greenville, South Carolina, USA. The two vessels are expected to be in operation by the end of 2022 and will expand the company's HIP capacity to focus on developments in Additive Manufacturing and advanced materials.

Bodycote's Greenville facility is Nadcap accredited and holds a number of core OEM approvals. The site consists of numerous vacuum furnaces and other capabilities suited to support Bodycote's customers. The Greenville site will serve aerospace, defence, medical and general industrial customers throughout the Southeastern region.

Bodycote states that it operates the world's largest network of HIP equipment, having more than fifty HIP vessels of varying sizes in multiple locations. Processing capability can accommodate components that are nominally up to 198 cm in diameter by 366 cm high, and weighing over 30,000 kg.

Stephen Harris, Bodycote Group Chief Executive, "We are pleased to address our customer needs by bringing HIP services closer to their facilities. With the largest HIP operational capacity in the world, our continued investment demonstrates Bodycote's commitment to align resources to serve our customers across North America."

www.bodycote.com

ASH Industries' $5M investment to double workspace

ASH Industries, Lafayette, Louisiana, USA, a custom moulding manufacturer which offers in-house Metal Injection Moulding, thermoplastic and silicone injection moulding, reports that it will invest $5 million to expand its facility in Lafayette. The investment will see an additional 1,860 m^2 of workspace, new equipment and create eighty-five new jobs.

Established in 1991, the company also offers rotational moulding and tooling, cast epoxy components and seven-axis Swiss lathe production. In addition to this, ASH Industries, offers component assembly, secondary processing and decorating, utilising the latest in CNC, EDM and modelling technology.

"ASH Industries is optimistic about the future of manufacturing in Louisiana and so far has launched phase one of a three-phase programme to invest in jobs in our community," commented Hartie Spence, president of ASH Industries. "The ingredients of economic development in our industry are manufacturing space, a solid employee base and the latest in cutting-edge manufacturing equipment. ASH's current expansion will directly support and increase the services that we can provide customers who appreciate the benefits of having their products manufactured in our state."

To secure ASH's expansion in Lafayette, the State of Louisiana offered the company an incentive package that includes the services of LED FastStart, a workforce development programme. ASH Industries is also expected to participate in the state's Enterprise Zone and Industrial Tax Exemption programmes.

"The expansion of ASH Industries is an important job creation project for the skilled workforce in Lafayette," stated Louisiana Governer John Bel Edwards. "For more than thirty years, ASH has fostered a strong team, and is set to grow that team further – a testament to the opportunities available in Louisiana's manufacturing industry."

Lafayette Mayor-President Josh Guillory added, "ASH Industries has consistently grown since opening its doors in Lafayette thirty-one years ago, and expanding its operations will lead to continued success for its employees, their families and our community. This multi-million-dollar investment will not only benefit ASH Industries but Lafayette as a whole by stimulating economic growth and creating competitive job opportunities."

www.ashindustries.com ■

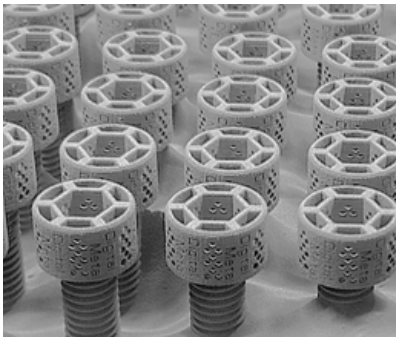
Markforged completes Digital Metal acquisition

Markforged, headquartered in Watertown, Massachusetts, USA, has announced that it has successfully completed the acquisition of Digital Metal from Höganäs AB, Sweden, for around $32 million in cash, 4.1 million shares of Markforged common stock and approximately $1.5 million in cash to settle intercompany balances. Digital Metal, and its team of professionals, will continue to operate under the Digital Metal brand as a subsidiary of Markforged.

Founded in 2003, Digital Metal was a wholly-owned subsidiary of Höganäs AB and developed a proprietary Binder Jetting technology reported to enable the production of highly complex, precision metal components with superior surface finish, part quality and reliability. The company's BJT capabilities for production-grade parts enable manufacturers to produce high volumes of functional metal parts from a variety of metals, including stainless steels, titanium and copper.

Digital Metal machines have been used to produce hundreds of thousands of parts, including parts for leaders in consumer products, academia, and the automotive industry. Markforged sees significant opportunities to further accelerate Digital Metal adoption through integrated software capabilities and a global go-to-market engine.

"We are excited to successfully complete the acquisition of Digital Metal, and officially welcome its team to Markforged," stated Shai Terem, president and CEO of Markforged. "Together, we will continue advancing our vision for distributed manufacturing by bringing the high volume production of precise metal parts directly to the point of need. By integrating Markforged's software capabilities and global go-to-market engine with Digital Metal's precise and reliable Binder Jetting solution, we expect to unlock significant opportunities to further accelerate Digital Metal adoption into our existing and future customers."



Digital Metal's Binder Jetting enables the production of precision metal components (Courtesy Digital Metal)

www.markforged.com
www.digitalmetal.tech

Nano Dimension expands into ceramic and metal AM with acquisition of Admatec and Formatec

Nano Dimension Ltd, Waltham, Massachusetts, USA, a specialist in additively manufactured electronics and micro Additive Manufacturing, has signed and closed a definitive agreement to acquire Formatec Holding B.V. (Admatec/Formatec) which includes its two subsidiaries: Admatec Europe B.V. and Formatec Technical Ceramics B.V. Admatec/Formatec, based in the Netherlands, is a developer and manufacturer of Additive Manufacturing machines for ceramic and metal components. Its industry-grade systems use a form of Vat Photopolymerisation (VPP) and materials with superior mechanical, electrical, thermal, biological, and chemical properties to produce a range of parts for medical, jewellery and industrial uses.

Admatec/Formatec's service bureau platform combines the advantages of Metal Injection Moulding and Additive Manufacturing for industrial-scale customers. Both means of production have served as a strategic advantage in working with customers, from early-stage ideas into serial production of end-use parts. Nano Dimension will further expand this reach through its experience in deep learning-based AI, materials science and robotics.

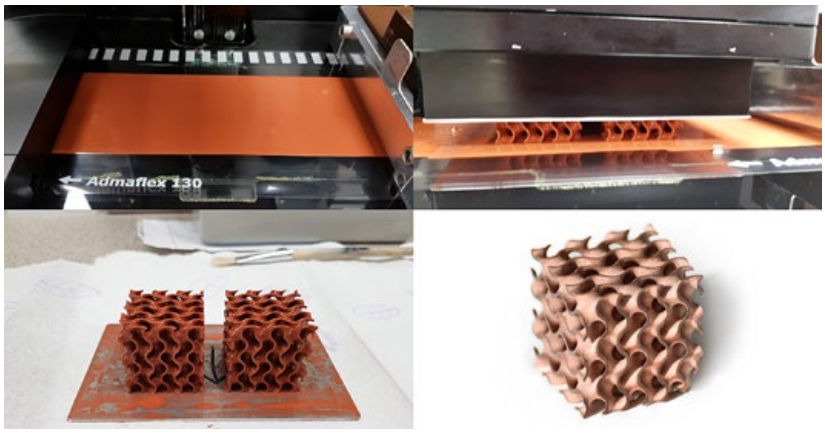
Admatec/Formatec has shown promising financial results under strenuous circumstances of its parent company, indicating that growth based on its innovative technology is reliably expected. The business delivered $5.3 million in revenue with a gross margin of 56% in 2021 and is expected to grow annually. Nano Dimension has paid a total cash sum of $12.9 million for Admatec/Formatec (net of its cash).

Jaco Saurwalt, Chief Operating Officer of Admatec/Formatec, who is joining Nano Dimension as the Head of its Admatec/Formatec Division, commented, "The teams across Admatec and Formatec are excited to become a part of Nano Dimension. We are proud of how we have developed this business and are convinced that we shall be able to expand and accelerate our growth based on our present technology and services. We expect that the combined expertise with Nano Dimension will further establish a leading position in the high-mix-low-volume 3D-AM production markets."

Yoav Stern, chairman and Chief Executive Officer of Nano Dimension, stated, "Admatec/Formatec's scientists, engineers and other team members, all of whom joined Nano Dimension upon closing of this transaction, are leading experts and industry veterans in AM 3D-industrial processes. They are going to continue to be led by their present management team."

Stern added, "No less important, is our intention to use our deep learning-based artificial intelligence technologies, from our DeepCube acquisition, to become the 'robotic brains' for Admatec/Formatec systems. We expect this will improve yield and throughput and drive a more seamless integration with Nano Dimension's Fabrica systems."

www.admateceurope.com
www.nano-di.com



A sintered copper part additively manufactured on the Admaflex 130 (Courtesy Admatec Europe)

3DCeram Sinto acquires majority of Tiwari Scientific Instruments

3DCeram Sinto, Bonnac-La-Côte, France, has become the majority shareholder of startup Tiwari Scientific Instruments, Berlin, Germany, which will now be known as 3Dceram Sinto Tiwari.

Tiwari Scientific Instruments was founded in 2019 within the European Space Agency (ESA) ecosystem. The company works with all stages of Fused Filament Fabrication (FFF) Additive Manufacturing, a Material Extrusion (MEX) process. The company has successfully developed and commercialised a technology for the MEX AM of high-density metals and ceramics, and offers services and consultancy to companies interested in adopting the technology.

3DCeram Sinto's acquisition of Tiwari furthers its Multi Advanced Technology (MAT) development programme. This project aims to serve the objectives of a new form of additive and intelligent manufacturing, organised in networks and highly digitised, allowing better integration into industry 4.0 workflows.

www.3dceram.com
www.tiwari-instruments.com

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Sandvik reports solid demand throughout the business in Q2 2022

Sandvik AB, headquartered in Stockholm, Sweden, has released its interim report for the second quarter of 2022. Order intake was stated to be SEK 28,740 million, up 32% from the same period in 2021. Revenue amounted to SEK 27,050 million, an increase of 34% – or at fixed exchange rates an increase of 25%, of which organic growth was 6%.

"We have delivered another strong growth-quarter and despite the wide-scale macro imbalances we continued to see solid demand in our businesses. Many acquisitions were successfully completed last year, all of which strengthen our offering and positions. These too have contributed to the solid growth of the top line," stated Stefan Widing, Sandvik's president and CEO.

Adjusted EBITA amounted to SEK 5,141 million, corresponding to a margin of 19%. Items affecting comparability amounted to SEK -1.1 billion mainly related to the wind-down in Russia. "The pausing of the business in Russia, eventually followed by the decision to wind down, has naturally impacted the development. Excluding Russia, both order intake and revenues grew organically by 10%, the sixth consecutive quarter of double-digit organic growth," continued Widing.

Excluding Russia, both order intake and revenues grew organically by 10%, reported to be the sixth consecutive quarter of double-digit organic growth. Profit for the period amounted to SEK 2,627 million, down from SEK 3,159 million in Q2 2021.

Following the announcement last year that Sandvik Materials Technology is to be listed as a separate company and rebranded Alleima, Widing stated, "This will be the last quarter I will comment on Sandvik Materials Technology's performance, as the separation is closing in, planned on August 31 this year. Overall, the market demand was strong and broad-based, with an increased number of umbilical orders. Organic order intake grew 26% year on year and, excluding major orders, growth was 21%."

Concluding, Widing added "We have experienced solid demand throughout the business, with regional disruptions distorting the overall performance. On a broader scale, macro-economic imbalances must be managed, but we have continued to stay focused on the business and executed on our shift to growth strategy. We have a clear set of strategic ambitions and new financial targets, for which there is a strong commitment to deliver on. Even though uncertainties lie before us, I am confident that our leading positions, the work we have done to become more resilient, and our experience and agility will enable us to deliver on these targets."

www.home.sandvik/en

Ceramic Additive Manufacturing project receives grant to turn CO_2 into clean energy

Researchers from Cornell University, Ithaca, New York, USA, are partnering with Lithoz America, Troy, New York, and Dimensional Energy, a Cornell startup also based in Ithaca, to develop additively manufactured ceramics that can be used in a process that turns carbon emissions into clean energy. Led by Dr Sadaf Sobhani, assistant professor of mechanical and aerospace engineering at Cornell University, the project has been awarded a $50,000 grant from FuzeHub, a not-for-profit organisation established to help business growth in New York state.

Dimensional Energy is reported to use energy reactors to convert carbon dioxide into chemicals that can be processed into greener fuel for the aviation industry. The company has seen support from United Airlines and other investors, but still faces challenges in scaling its technology.

"Excellent thermal properties and corrosion resistance make ceramics attractive for these reactors, but significant design constraints limit their actual performance," Sobhani stated. "The freedom of design and choice of materials enabled by ceramic Additive Manufacturing will narrow the theory-performance gap to hit the desired milestones."

The FuzeHub grant will be used to develop advanced ceramics for Additive Manufacturing that are better able to withstand the operating environments of clean energy reactors, targeting specialised thermocatalytic reactors like those used by Dimensional Energy.

"I'm really looking forward to bringing our research to a market setting, and in particular to help create more environmentally responsible fuels and chemicals," Sobhani added.

Elena Garuc, Executive Director, FuzeHub, concluded, "Stronger domestic production supports a more resilient economy. During this round of Manufacturing Grants, many of the projects that were selected involved advanced materials. As awardees work to solve technical challenges, they're also supporting the onshoring of production, which is crucial for supply chain resiliency, especially in these post-pandemic times."

www.cornell.edu
www.lithoz.com
www.dimensionalenergy.com

PowderMet2022: An upbeat assessment of the North American MIM industry

The PowderMet2022: International Conference on Powder Metallurgy & Particulate Materials, and the co-located AMPM2022: Additive Manufacturing with Powder Metallurgy Conference, was held in Portland, Oregon, USA, from June 12–15, 2022. Organised by the Metal Powder Industries Federation (MPIF), the event included three days of presentations accompanied by an exhibition and a range of social and networking events.

The Opening General Session included a presentation by MPIF President Rodney Brennen, who gave delegates a detailed overview of the state of the North American Powder Metallurgy industry.

"The North American Powder Metallurgy industry has not been immune from the unprecedented challenges facing the global supply-chain. We continue to feel the negative effects of the COVID-19 pandemic," began Brennen.

The semiconductor microchip processor shortages also had a major impact on the PM sector, and continues to cause delays in automotive production. "Most automotive companies, whose vehicles use an estimated 20-100 processors each, depending on the vehicle's features, agree that recovery will begin in the second half of 2022, but a normal supply won't be met until well into 2023. Volkswagen doesn't expect demands to be met until 2024," Brennen explained.

PowderMet2022 included a presentation on the state of the North American Powder Metallurgy industry by MPIF President Rodney Brennen

However, regarding the MIM industry, Brennen provided a more positive outlook. "The MIM industry continues to be robust, as evidenced by the successful MIM conference earlier this year. Most MIM parts producers continue to experience double-digit growth."

The MPIF estimates that US MIM sales in 2021 reached $520 million, compared to pre-pandemic figures, published in the MPIF's 2020 State of the PM Industry report, estimated to be in the range of $460 to $480 million in 2019.

"The medical and firearms sector continue to be the prime consumers of MIM components. Even better, the demand for general industrial applications and automotive MIM components continues to increase annually," stated Brennen.

Due to the similar powder grades used for both MIM and metal Additive Manufacturing applications, the MPIF reported combined powder shipment figures. The total 2021 North American MIM and AM powder shipments were said to have increased by an estimated 5–10% to 3,934,767–4,202,178 kg. Of this amount, it was stated that an estimated 360,000 kg is dedicated to AM.

"Improving powder quality will benefit both MIM and AM. A narrower particle size distribution range, greater sphericity, fewer satellites, and less internal porosity will improve throughput, mechanical properties, and overall process consistency," added Brennen. "Typically, these powders are manufactured by gas atomisation, but capacity has been added recently for plasma atomisation and research continues to develop water-atomised low-alloy materials for MIM and AM."

"Normal business challenges faced by MIM companies, such as the continuing need for skilled employees, global competition, and rising raw materials costs, have been replaced by the more immediate supply-chain crunch and long-term concerns regarding the effect metal AM growth will have on raw materials availability," concluded Brennen.

www.mpif.org

Desktop Metal qualifies nickel alloy Inconel 625 across range and updates Live Sinter software

Desktop Metal, headquartered in Boston, Massachusetts, USA, has announced the qualification of nickel alloy Inconel 625 for its Studio System™ 2 and its Shop System metal Additive Manufacturing machines, resulting in the material's qualification across its entire metal AM portfolio, which includes the Production System and X-series models. Desktop Metal also announced updates to Live Sinter, the company's sinter simulation software application.

"Manufacturers looking to produce complex geometries in IN625 now have a one-stop shop for efficient Additive Manufacturing 2.0 production," stated Ric Fulop, founder and CEO of Desktop Metal. "IN625 is a very difficult material to machine, but our technology truly makes it easy. We are proud of the work our world-leading material and process teams have done ensuring that this popular material can be offered across our portfolio."

IN625 is a high-performance nickel alloy known for high levels of strength, temperature resistance, and corrosion resistance — making it a popular material choice for applications in the aerospace, chemical processing, and offshore energy industries.

Live Sinter simulation software

Launched in 2020, Live Sinter automates the generation of sinter-ready, buildable geometries, as well as supports, setters, and inserts, to make repeatable, volume production of high-precision end-use metal parts through sinter-based Additive Manufacturing more accessible.

"Within the field of sinter-based Additive Manufacturing, Live Sinter stands alone for its ease of use and functionality," commented Ric Fulop, founder and CEO of Desktop Metal. "No other solution offered today combines our powerful, rapid multi-physics simulation with scan-based adjustments and automated support and setter generation. Customers continue to report their absolute delight with this tool to us, and we look forward to continuing to invest in advancing Live Sinter to make sinter-based manufacturing accessible to an ever wider audience, including metal injection moulding customers."

www.desktopmetal.com

Bosch Advanced Ceramics reveals additively manufactured microreactor

Bosch Advanced Ceramics, Immenstadt, Germany, together with the Karlsruhe Institute of Technology (KIT) and BASF, Ludwigshafen, Germany, has successfully produced what is claimed to be the first additively manufactured microreactor made of technical ceramics.

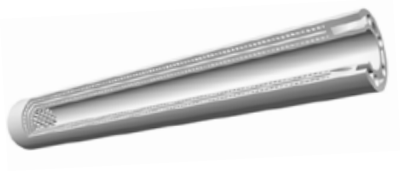
Microreactors are devices for housing chemical reactions. In terms of heat, stability and corrosion, few materials can withstand the extreme conditions caused by high-temperature chemical reactions. "To control and monitor a chemical reaction, a reactor needs to have hardness, heat resistance, and complex structures inside," stated Klaus Prosiegel, sales manager at the Bosch startup Advanced Ceramics, based in southern Germany. "3D printed technical ceramics bring these excellent properties to the table."

Bosch Advanced Ceramics was aware that technical ceramics are well suited for chemical reactions. "The challenge, however, lay in producing complex structures within the ceramic reactor," Prosiegel added. To solve this problem, the startup's ten-strong team combined their company's two core competencies of technical ceramics and Additive Manufacturing. "We've successfully employed 3D printing to produce ceramic components that can't be made by conventional means," he said.

BASF is now using this microreactor in basic research, since it allows the monitoring of chemical reactions under ideal temperature conditions. Furthermore, it requires fewer raw materials and less energy than large reactors. Experts can analyse these small-scale results and extrapolate them for large-scale implementation.

The next phase will be to additively manufacture a further ten to twenty reactors of the same design for BASF. In view of the potential applications for technical ceramics in the chemicals sector, Prosiegel sees a bright future, "After all, almost every laboratory crucible is made of technical ceramics," he added.

www.bosch-advanced-ceramics.com
www.kit.edu | www.basf.com



The microreactor enables monitored chemical reactions in a small space and is used in the chemical industry (Courtesy Bosch)

Quality monitoring during the ceramic production process (Courtesy Bosch)

Tekna announces two orders for its research-scale TEK15 plasma system

Tekna Holding ASA, Sherbrooke, Quebec, Canada, has signed contracts for the sale of two TEK15 research scale plasma atomisation systems which enable the development of highly spherical metallic or ceramic powders. The two systems will be used to produce spherical powder of various materials to be applied in Additive Manufacturing processes such as Binder Jetting, as well as Metal Injection Moulding.

The orders amount to a total value of $1.45 million and will be delivered to customers in early 2023. The systems will be used in a government research centre in Asia and by a private company in the USA for commercial R&D purposes.

"Our TEK15 system fosters innovation by enabling our customers to experiment with many different materials," stated Romain Vert, Director of System Sales at Tekna. "The system has been developed to allow users to explore different plasma environments and conditions and make swift adjustments to produce different variations of materials. These agreements take the number of units sold up to fifty-seven and correspond with the increased demand Tekna is experiencing for its advanced materials."

www.tekna.com

Tekna will sell two TEK15 plasma systems which will be used for R&D purposes (Courtesy Tekna Holding)

Furnace manufacturer Nabertherm celebrates two anniversaries

In September 2022, Nabertherm GmbH, Lilienthal, Germany, is celebrating its 75th anniversary.

In 1947, founder Conrad Naber manufactured the company's first preheating furnace for a dental laboratory from his parents' house. In 1951, the company moved into a shop, before relocating to Lilienthal with its twenty-five employees in 1954. Throughout its seventy-five years, the company has been led by Naber, Friedrich-Wilhelm Wentrot and Timm Grotheer.

Currently, Nabertherm employs 500 people, runs subsidiaries in the most important global markets, and approximately 75% of industrial furnaces are now supplied internationally. The applications that the company supports today range from arts and crafts to foundries to fuel cells and sintering of Powder Metallurgy parts.

2022 also marks the 100th birthday of the company's late founder Conrad Naber.

www.nabertherm.com

ASM International announces key changes to its leadership structure

ASM International has announced Kelvin Scott (left) as CIO and Ryan Milosh (right) as COO (Courtesy ASM International)

ASM International has announced two key changes to the Society's leadership structure, with the promotion of Ryan Milosh to Chief Operating Officer and the addition of Kelvin Scott as Chief Information Officer. ASM International is the world's largest professional technical society serving the needs of scientists, engineers, and technicians who develop, test, select, and apply advanced materials, including metals, composites, polymers, and ceramics.

As Chief Operating Officer, Milosh will be responsible for oversight of all ASM International operations, except the Data Ecosystem and Information Technologies groups. In his most recent position, Milosh has served the organisation as Chief Sales and Marketing Officer. He has a wealth of experience in understanding industry requirements, building partnerships and collaborations, and launching new products and services.

Sandy Robert, Executive Director, will continue to work with Milosh on capabilities planning for the rest of the organisation with an eye to aligning the society with its lines of business and strategic priorities, as well as maximising its value to members and customers.

Scott is joining as a full-time staff member after five years in an IT counsel role with ASM International. His background includes more than twenty-two years of running international consulting businesses, providing IT strategy, enterprise architecture, and programme management. As Chief Information Officer, Scott will work across the organisation to develop and deploy ASM's digital strategies and information technology systems, both internal and customer-facing.

www.asminternational.org

Krahn showcases potential of Ceramic Injection Moulding to plastics industry

Krahn Ceramics GmbH, headquartered in Hamburg, Germany, will showcase its Ceramic Injection Moulding (CIM) solutions to an international audience at the leading plastic & rubber trade fair, K 2022, taking place in Düsseldorf, Germany, October 19-26, 2022.

"As a specialist for ceramic solutions based on Powder Injection Moulding technology, and part of the Otto Krahn Group, we can use our material and processing know-how and customise ceramic compounds to master challenges where plastics reach their limits," stated Dr Stefan Stolz, Managing Director.

"Ceramics can offer customers from the plastics sector the option of opening up new markets – in this, we provide support as an innovative technology partner along the entire value chain from powder to the finished parts."

In many applications where aesthetics play a major role, for example, in watchmaking and luxury automotive interiors, ceramics already play an important role. Ceramics are characterised by their durability; hardness; wear, corrosion, and temperature resistance, as well as a wide range of electrical properties.

Technical ceramics offer material properties that are ideal for high-performance applications, but Krahn also believes that they offer opportunities as an additional material offering for the plastics industry, as CIM feedstocks can be processed by the injection moulding processes already common practice for producers of polymer parts.

Krahn Ceramics specialises in the development and production of customised ceramic and metal compounds, which can be made according to customer requirements. As well as supplying ceramic powders, the company also provides its own binders and process additives, as well processing and technical support.

From its technical centre in Dinslaken, Krahn focuses on the production and development of binders and feedstock for both Powder Injection Moulding and ceramic Additive Manufacturing.

www.krahn-ceramics.com ■

Krahn Ceramics will showcase CIM solutions at a polymer trade fair K (Courtesy Krahn Ceramics)

Markforged updates binder in popular 17-4PH stainless steel filament

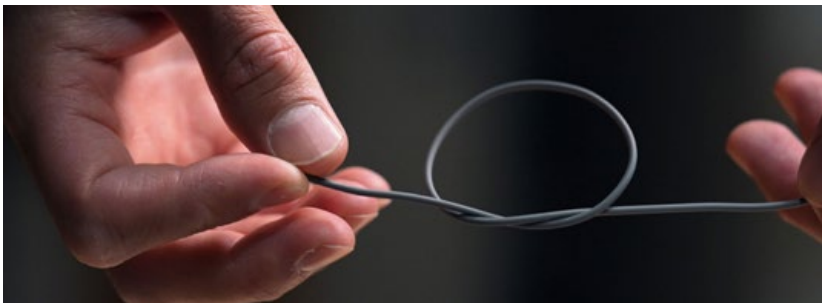
Markforged, headquartered in Watertown, Massachusetts, USA, has updated its 17-4PH stainless steel filament to offer increased flexibility, whilst maintaining the filament's original strength and the versatility of the material. The filament, used in Markforged's Metal X Additive Manufacturing machines, features the same metal powder with an updated binder material.

17-4PH is a general purpose stainless steel alloy, frequently utilised for its strength and ability to withstand significant wear, heat, and corrosion. It can be heat treated, polished, machined, welded, and additively manufactured. It is often used for industrial applications such as grippers, lathe jaws, fixtures, brackets, high-wear tooling, functional prototypes, and custom wrenches & sockets.

Markforged states that the 17-4PH filament is the Metal X System's most popular metal material. Altering the composition of the binder, with a new material and percent volume, preserves the original filament's strength, durability, and corrosion resistance, yet offers significantly more flexibility and a less brittle filament. The updated version v2 also features improved mechanical properties with better isotropic characteristics.

The v2 formulation is also faster to load and comes in larger spools, explains Markforged. It can be loaded into an unheated chamber, and used for twice as long before the spool of filament must be replaced. This is said to significantly reduce startup and material changeover times.

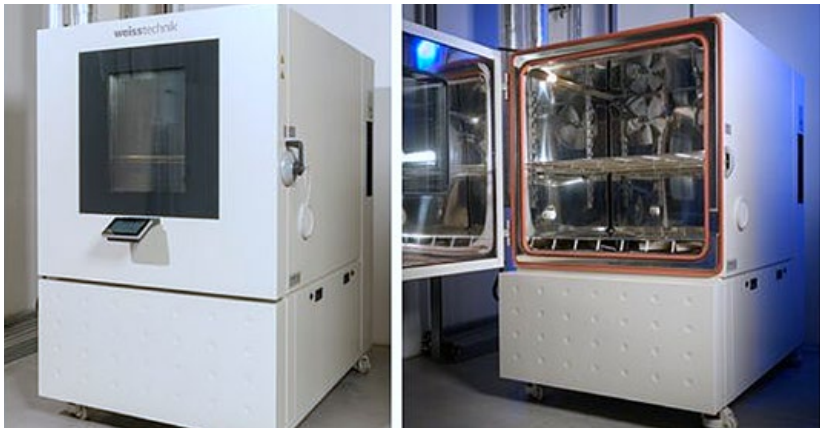
www.markforged.com ■



Markforged has updated its 17-4PH stainless steel filament to offer increased flexibility, whilst maintaining its strength and versatility (Courtesy Markforged)

Climatic chamber for conditioning metal powders installed at TWI

TWI, Cambridge, Cambridgeshire, UK, has acquired a climatic chamber from Weiss Technik, Germany, for the conditioning of metal powders. The new climatic chamber will be used to assess the influence of storage conditions, such as the effect of humidity and temperature, on metal powders as part of IUK funded Scalable AM Rule Creation & Dissemination (SAMRCD) project.



TWI will use the Weiss Technik climatic chamber to assess the influence of storage conditions, such as the effect of humidity and temperature, on AM metal powders (Courtesy TWI)

The climatic chamber is capable of simulating various environmental conditions, due to its extended temperature and humidity ranges. Additionally, the climatic chamber allows for rigorous checking and regulation of testing parameters to ensure simulation conditions meet the necessary requirements.

The SAMRCD project operates through a consortium led by Authentise Ltd, London, UK, having been awarded a competitive grant by the UK Research and Innovation's (UKRI) Transforming Foundation Industries challenge, delivered by Innovate UK. TWI will also use the new climatic chamber to help customers simulate a particular environment for metal powders, simulate storage or operating conditions. It will help assess corrosion resistance, evaluate thermal stress and distortions, and understand coating thermal shock response.

www.weiss-technik.com/en
www.twi-global.com

Martin Back appointed as Managing Director of BASF 3D Printing Solutions

Forward AM, the Additive Manufacturing solutions brand of BASF 3D Printing Solutions GmbH, headquartered in Heidelberg, Germany, has announced that Martin Back has assumed the role of Managing Director of BASF 3D Printing Solutions as of August 1, 2022, following François Minec's decision to leave this role and the company, which went into effect on May 31, 2022.

Minec held the position of Managing Director since April 2019 and set the company on a growth track by accelerating the commercialisation of Additive Manufacturing. It was stated he will continue his commitment to industrialising Additive Manufacturing and plans to remain in the industry.

With twenty-five years of industry experience in management roles, Back is familiar with the additive and manufacturing industries, having already served as Managing Director of BigRep GmbH from 2018 to 2021.

It is reported that Volker Hammes, Managing Director BASF New Business GmbH and chairman of BASF 3D Printing Solutions GmbH will ensure a smooth transition period. Minec will support Back during the start of his new role. The strategic direction of BASF 3D Printing Solutions will remain unchanged and continue aiming at industrialising Additive Manufacturing.

Back commented, "I am honoured to take over responsibility at BASF 3D Printing Solutions. I am thrilled to actively contribute to the growth of the Additive Manufacturing business together with our global customer base and established partner network."

www.forward-am.com

Sintex celebrates twenty-five years

Sintex a/s, headquartered in Hobro, Denmark, recently celebrated its twenty-fifth anniversary. As part of its celebration, the company welcomed the families of its employees into the facility and announced a DKK 25,000 donation to provide direct emergency relief to Ukraine.

A Grundfos Group business, Sintex manufactures and supplies a range of Powder Metallurgy components, including Metal Injection Moulding, stainless steel parts, sintered stainless steel filters, metal spraying, soft magnetic composites and permanent magnetic systems such as magnetic couplings and magnetic rotors. The company supplies to a wide variety of industries across the world. Applications include components for the automotive sector, motors and pumps, medical sector, electronics and energy industries.

www.sintex.com

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Emery Oleochemicals and 3DGence partner to develop sinter-based material extrusion process

Emery Oleochemicals, Düsseldorf, Germany, and 3DGence, headquartered in Przyszowice, Poland, have announced a strategic partnership for Additive Manufacturing. Both companies are active in the development and use of filaments for sinter-based Material Extrusion (MEX), or Fused Filament Fabrication (FFF), and together they aim to enable customers to produce individual high-performance, affordable parts and realise mass applications with Additive Manufacturing.

"Emery Oleochemicals and the entire team are proud to continue developing innovative processes of binder-based FFF printing together with 3DGence," stated Patrick Folkert, Manager of Additive Manufacturing at Emery Oleochemicals. "We will contribute our technical expertise and are excited about adding a superior solution to the market."

Through an iterative design process, 3DGence has developed and launched Element MP260 and MP350 Additive Manufacturing machines specifically for sinterable filaments. These machines enable Additive Manufacturing on an industrial level with a reported high surface quality. The machines have been tested by MIM industry partners to meet rigorous process requirements for filaments in order to make Additive Manufacturing machines more reliable and easy to use.

Emery Oleochemicals has supplied its binder system to the powder injection industry over thirty years. This binder system is said to be applicable to almost all sinterable materials to create entirely new opportunities for the industry and eliminate the need for expensive material development for other Additive Manufacturing options. It is possible to process known sinterable materials at low cost while gaining a market advantage both in terms of time and efficiency of existing resources; the option to directly use materials in prototyping and low- to mid-volume production is intended to enable engineers new opportunities to significantly reduce time-to-market.

Filip Turzyński, R&D Manager, 3DGence, added, "With the 3DGence Element MP260/MP350 printers, we have developed a system specifically for metal/ceramic filament printing which is based on a strong binder system. Therefore, it was a logical step for us to enter a strategic partnership with Emery. They offer the best and most versatile binder system on the market. We want to – and will – go further together."

greenpolymeradditives.emeryoleo.com/3dprinting

www.3dgence.com

Peter Vervoort dies following tragic accident

It is with much sadness that we report the death of Peter Vervoort who passed away on Sunday, August 7, following a fatal cycling accident. He was fifty-four.

Peter was known to many in the Powder Metallurgy industry having spent the majority of his career working in the furnace sector. He was a regular at PM events, always approachable and keen to share his knowledge and advice.

Born in 1967 in Rozenburg, the Netherlands, Peter studied Materials Science and Engineering at the Technical University Delft. On completing his degree, he remained at TU Delft as an Associate Scientist, working in the field of Metal Injection Moulding.

Peter Vervoort died following a fatal cycling accident

In 1996 he joined Cremer Thermoprozessanlagen GmbH, where he was Assistant General Manager. In 2002, he moved to Elino Industrie-Ofenbau as head of Powder Metallurgy processing, before advancing to Group R&D Manager in 2010.

From 2011 to 2013, Peter ran the Metal Injection Moulding department at ITB Precisietechniek B.V., before joining Eisenmann Thermal Solutions GmbH in 2013 as VP Process Development. When Eisenmann was acquired by Korea's Onejoon in 2020, Peter remained at the company as VP Global Technology.

Peter was a keen cyclist and runner, with a passion for the outdoors. He leaves a wife and four children.

He will be sadly missed by all his family, friends and colleagues.

ASTM proposes standard to define properties of filaments for Additive Manufacturing

ASTM International's Additive Manufacturing committee (F42) has announced that it is developing a new material testing standard for tensile properties of filaments for Additive Manufacturing.

This proposed standard – WK82320 – could be used to determine basic performance information on the raw materials used in filament-based Material Extrusion (MEX) machines, known widely as Fused Filament Fabrication (FFF) machines.

"[The standard] can help users from labs to industries – especially aviation, aerospace, automotive, and defence – to select the filament that meets their requirements. It can also facilitate quality control and optimization of filament production for the manufacturers," stated Haibin Ning, the ASTM International member leading the development effort.

This effort directly relates to United Nations Sustainable Development Goals #9 (Build resilient infrastructure, promote sustainable industrialisation and foster innovation) and #12 (Ensure sustainable consumption and production patterns).

www.astm.org

Quintus delivers HIP to TAG Medical for post-processing MIM components

Quintus Technologies, Västerås, Sweden, reports that it has recently delivered a QIH 15L Hot Isostatic Press (HIP) to TAG Medical Products Corporation, Ltd, Ga'aton, Israel. The new press will be used to ensure that MIM implants and surgical tools produced at TAG Medical possess the maximum theoretical density, ductility and fatigue resistance required for use in the demanding medical sector.

"To increase production capacity, we invested in a new MIM production line," stated Ran Weizman, Executive VP at TAG Medical. "The Quintus press will serve us for the implants and minimal cutting tools production, where high material uniformity and good mechanical properties are required."

The QIH 15L Hot Isostatic Press features include High Pressure Heat Treatment™ (HPHT™) and Uniform Rapid Quenching (URQ®), enabling the press to produce finished MIM parts which meet the required density, ductility and fatigue requirements. Incorporating heat treatment and cooling in a single process, HPHT combines stress-relief annealing, HIP, high-temperature solution annealing, high-pressure gas quenching, and subsequent ageing or precipitation hardening in one integrated furnace cycle.

A Quintus press model QIH 15L has been delivered to TAG Medical Products (Courtesy Quintus Technologies)

The consolidation of multiple steps in the HIP allows several functions to be performed in a single location, with fewer pieces of equipment on the production line. This was said to be a central consideration for TAG Medical in selecting this technology.

"All TAG manufacturing processes, from A to Z, are done under one roof. Therefore, it is important for us to work with equipment that gives us this option," added Weizman.

With a new emphasis on disposable surgical instruments in TAG's MIM production chain, faster throughput and higher workpiece quality are also essential. The QIH 15L's URQ capability achieves an impressive cooling rate of > 80K/s while minimising thermal distortion and non-uniform grain growth. The press's furnace chamber has a diameter of 170 mm and a height of 290 mm and operates at a maximum pressure of 30,000 psi and a maximum temperature of 1,400°C.

"Quintus is the global leader in HIP technology," noted Weizman. "We visited their factory a few years ago and were impressed with the company's professional team, customer centre, and production lines. Accurate, well controlled, and user friendly – the Quintus press meets all the above requirements."

Jan Söderström, CEO of Quintus Technologies, concluded, "Our presses are designed to enhance efficiency and lower per-unit processing costs while saving space, energy, and infrastructure. These are important benefits for companies like TAG Medical that are looking ahead to mass production of development-stage products and expansion of their OEM business. We are delighted to be working with TAG as it continues to develop solutions that improve quality of life, reduce costs, minimise surgery times, and save lives."

www.quintustechnologies.com
www.tag-med.com

PowderMet2023 issues call for papers

The programme committee for the International Conference on Powder Metallurgy & Particulate Materials (PowderMet2023), which is scheduled to take place at Caesars Palace, Las Vegas, Nevada, USA, from June 18-21, 2023, has issued a call for papers and presentations covering the latest developments in Powder Metallurgy materials, processes, and applications.

Sponsored by the Metal Powder Industries Federation (MPIF) and its affiliate APMI International, the four-day event is co-located with the Additive Manufacturing with Powder Metallurgy Conference (AMPM2023).

Abstracts covering any aspect of PM and particulate materials technology are invited, including the following:

- Powder injection moulding (metals & ceramics)
- Design & modelling of PM materials, components & processes
- Particulate production
- General compaction & forming processes
- Pre-sintering & sintering
- Secondary operations
- Materials
- Refractory metals, carbides & ceramics
- Advanced particulate materials & processes
- Material properties
- Test & evaluation
- Applications
- Management issues

The abstract submission deadline is November 5, 2022. Further details are available through the conference website.

www.mpif.org

Ames Laboratory changes name

Ames Laboratory, Ames, Iowa, USA, has changed its name to Ames National Laboratory. According to representatives from the US Department of Energy Office of Science, Iowa State University, and Ames National Laboratory leadership, the change has been made to more accurately reflect the institution's past, present, and future role as a DOE National Laboratory.

Ames National Laboratory creates innovative materials, technologies, and energy solutions and has undertaken a large number of AM R&D projects in recent years.

"The new name honours the rich history of scientific discovery at Ames, and it also emphasises the institution's respected role as one of our seventeen National Laboratories, now and into the future," stated Geri Richmond, Under Secretary for Science and Innovation at the DOE.

www.ameslab.gov

www.energy.gov

Blue Power and Indutherm launch atomisation system for platinum and high temp alloys

Blue Power Casting Systems GmbH, Walzbachtal, Germany, has launched a new high-temperature gas atomisation system for platinum and other high-melting alloys following a collaboration with Indutherm Casting Technology, a fellow subsidiary of Indutherm Erwärmungsanlagen GmbH.

This development is the result of a German-Canadian research project titled HiPTSLAM which began in 2019. Indutherm Casting Technology participated in the project along with research institutions, producers and end-users to collectively identify new tool steel solutions. Indutherm's task was the process optimisation in the high-temperature atomisation of steel, CoCr, etc. and was carried out in close cooperation with Rosswag Engineering, also a HiPTSLAM member.

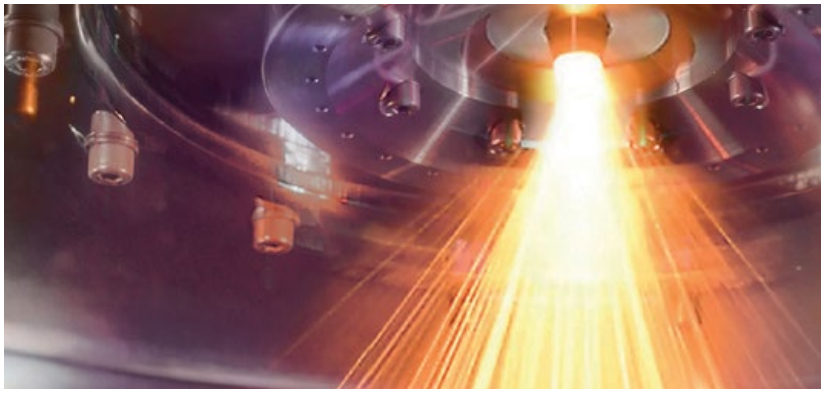
This research resulted in the development of new HTC versions of the company's AUG series of gas atomisers. With direct inductive heating, the HTC+ version now reaches a maximum temperature of 2100°C. Oxidation-free processing in the closed-chamber machine by means of degassing, vacuum and protective gas features is said to guarantee maximum purity of the produced powder.

The AUG HTC+ produces fine powders < 20 µm from high melting special alloys e.g., based on platinum or chrome for a wide range of powder applications such as Laser Beam Powder Bed Fusion (PBF-LB), Metal Injection Moulding, Binder Jetting (BJT) and more. Three different AUG versions are available in the HTC+ specification, offering capacities from ≈ max. 6 kg Pt (AUG 500 HTC+) to ≈ max. 70 kg Pt (AUG 3000 HTC+).

Atomisation tests with up to 20 kg of 950 PtCu, 950 PtRu, 900 PtRh and with pure platinum have showed high process stability and excellent results in terms of particle size distribution, purity and flowability. This is said to open numerous new application possibilities in the areas of watch and jewellery production, medical technology, aerospace and more. Additionally, material loss is a key factor, especially when it comes to precious metals. The machine is designed for easy cleaning and is equipped with a gas separation system (by treatment in a cyclone) and a filtration system.

The new high-temperature atomisers are said to have been met with great interest in the field of materials research, as they also have the best prerequisites for the atomisation of metal-ceramic compounds, intermetallic compounds, or high-entropy alloys.

www.bluepower-casting.com
www.indutherm.de/en/



Blue Power Casting Systems and Indutherm Casting Technology have launched an atomisation system for platinum and other high melting alloys (Courtesy Blue Power Casting Systems GmbH)

LÖMI joins ColdMetalFusion Alliance

LÖMI GmbH, a supplier of debinding machines based in Grossotheim, Germany, reports it has joined the ColdMetalFusion Alliance, an industry alliance of leaders with experience in the fields of sintering, Additive Manufacturing and traditional industrial manufacturing.

"Debinding of metal parts is part of our DNA, and we have a long history of collaborating with the industry from large scale chemical site-projects down to producing our renowned all-in-one debinding stations," stated José Manuel Dias da Fonseca, CEO of LÖMI. "As we join forces with the other ColdMetalFusion partners, we want to elevate metal Additive Manufacturing to a more robust and reliable alternative to injection moulding. Together with the ColdMetalFusion partners, LÖMI will provide complete industrialised system solutions and deliver its know-how in sintering to the world's factory floors. We understand ourselves as the industry's partners."

ColdMetalFusion's vision is to industrialise Additive Manufacturing through common standards between sintering and Additive Manufacturing, as well as a common industrial culture and mindset.

LÖMI's solvent debinding systems are available from 15 to 1200 litres of batch-loading volume, from tabletop units to fully automatic systems, and can be extended on a modular basis. This enables customers to increase the productivity while improving their efficiency.

ColdMetalFusion members intend to demonstrate the Alliance's mission of industrialisation at Formnext 2022, which is scheduled to take place November 15-18 in Frankfurt am Main, Germany.

www.coldmetalfusion.am
www.loemi.com

Alstom collaborates with Replique for serial-production train part using AM

Transportation company Alstom, Mannhein, Germany, has utilised Replique's on-demand Additive Manufacturing platform to produce a batch of customised, industrial-grade serial parts. By digitising its supply chain, Alstom states that it is now able to produce small batches on demand and decentrally.

Established in 2020 as part of BASF's Digital Transformation initiative, Replique provides what it states is the first fully encrypted AM platform that makes spare part management more sustainable. By combining its digital inventory and a network of Additive Manufacturing professionals, it offers an end-to-end solution from qualification to production and shipment.

In train manufacturing, small batch sizes lead to high manufacturing costs due to the production of moulds and other tools. Additive Manufacturing can solve this challenge by eliminating fixed costs, resulting in parts that can be produced economically even in small quantities. Alstom explains that it has already taken advantage of the technology within the production of spare parts. Now, they can also fulfil specific customer needs using additive serial production.

Alstom operates globally, which means each train component has different requirements. They need a scalable solution for decentralised manufacturing in industrial-grade quality. Alstom works closely with Replique, leveraging the capabilities of an Additive Manufacturing network where all partners are carefully selected and qualified.

"The Additive Manufacturing market is still very fragmented, which makes it impossible for end-users to find an optimal solution for each part," commented Ben Boese, 3D Printing Hub Manager at Alstom Transport Deutschland GmbH. "With Replique, we benefit from all major Additive Manufacturing technologies and materials from a single source. In addition, we receive optimal technological preparation."

In order to meet a specific customer request, Alstom required several doorstoppers for a partition door that divides the passenger compartment of a diesel multiple unit into a first and second class. The small number of such components is usually an obstacle to initial production as well as project delays resulting in long delivery times. It is for this reason that Alstom selected Additive Manufacturing for the production.

Replique assisted Alstom with material and technology selection and was able to qualify and deliver the doorstopper for serial production within just one and a half months. During this process, the doorstopper went through the protocols of initial sample testing and assembly and received the final approval for series production.

"We were able to produce the doorstopper in a cost-neutral manner compared to conventional methods. Within the near future, we plan to further exploit the technology's potential by creating topology-optimised designs of new parts, or even make them lighter by using reduced infill," Boese added.

To enable on-demand production, careful qualification, including the selection of the right material, was crucial. The doorstopper not only had to fulfil its function over the entire service life of the train, but also meet high aesthetic standards, as a visible part inside the train compartment.

Stainless steel was chosen in order to meet these requirements. Using Material Extrusion (MEX) Additive Manufacturing processes, with Ultrafuse® 316L from Forward AM, a brand of Replique's material partner BASF 3D Printing Solutions, followed by debinding and sintering, Replique states that it was able to significantly reduce costs compared to other Additive Manufacturing methods.

Replique was able to qualify and produce its additively manufactured doorstopper for serial production within a month and half (Courtesy Alstom)

"Alstom has already shown in the past how 3D printing can be integrated in a lean and cost-efficient way. They are pioneers in Additive Manufacturing, and we look forward to supporting them on their journey to simplify and fully digitise their supply chain for all printable series and spare parts," commented Dr Max Siebert, CEO and founder of Replique.

Boese added, "Additive Manufacturing is now a key part of our supply chain. With Replique, we benefit from 3D printing and materials expertise, as well as a decentralised manufacturing network covering all relevant locations and technologies. Their end-to-end services enable us to respond faster and more cost-effectively to different customer requirements."

www.replique.io
www.alstom.com

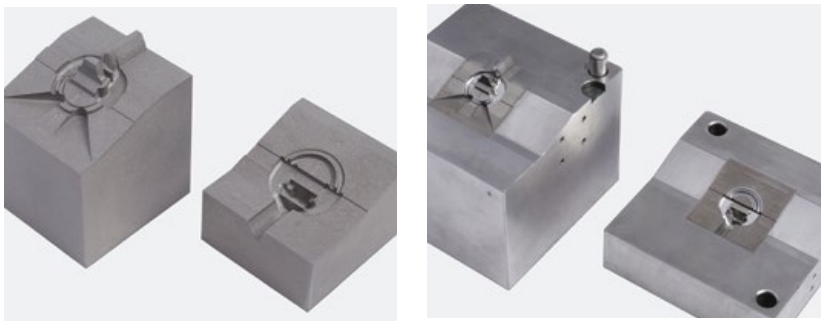
Mantle announces launch of its hybrid toolmaking system

Mantle, headquartered in San Francisco, California, USA, has announced the commercial launch and availability of its metal Additive Manufacturing system developed specifically for the toolmaking sector. Designed to simplify the production of mould and tool components, Mantle's AM process is said to reduce the time it takes to create tooling by eliminating or reducing many of the operations traditionally required to make precise, durable steel tool components.

Mantle uses its proprietary TrueShape technology – a hybrid Material Extrusion (MEX), CNC and sinter-based process. The system includes its P-200 Additive Manufacturing machine, built on a CNC platform, that integrates building and machining to produce parts with the accuracy and surface finish required for tooling.

A sintering stage follows using the company's F-200 furnace. This furnace can sinter multiple parts and will support multiple AM machines. Mantle offers two tool steel materials, H13 and P2X (a steel comparable to P20), said to be durable, stable, and perform like traditional tool steels with secondary operations like machining, polishing, coating, and laser welding.

Mantle's new AM system features the P-200 AM machine and F-200 sintering furnace (Courtesy Mantle)



Left: Fathom's cavity and core inserts as additively manufactured with Mantle's TrueShape metal AM technology. Right: Cavity and core inserts after Fathom finished the additively manufactured inserts and assembled them in its modular mould system (Courtesy Mantle)

The commercial launch of the Mantle system follows a successful delivery of beta systems to a number of customers. One of these was Westminster Tool, a precision mould maker based in Plainfield, Connecticut, USA, which installed a beta system and is integrating it into its mould-making operations.

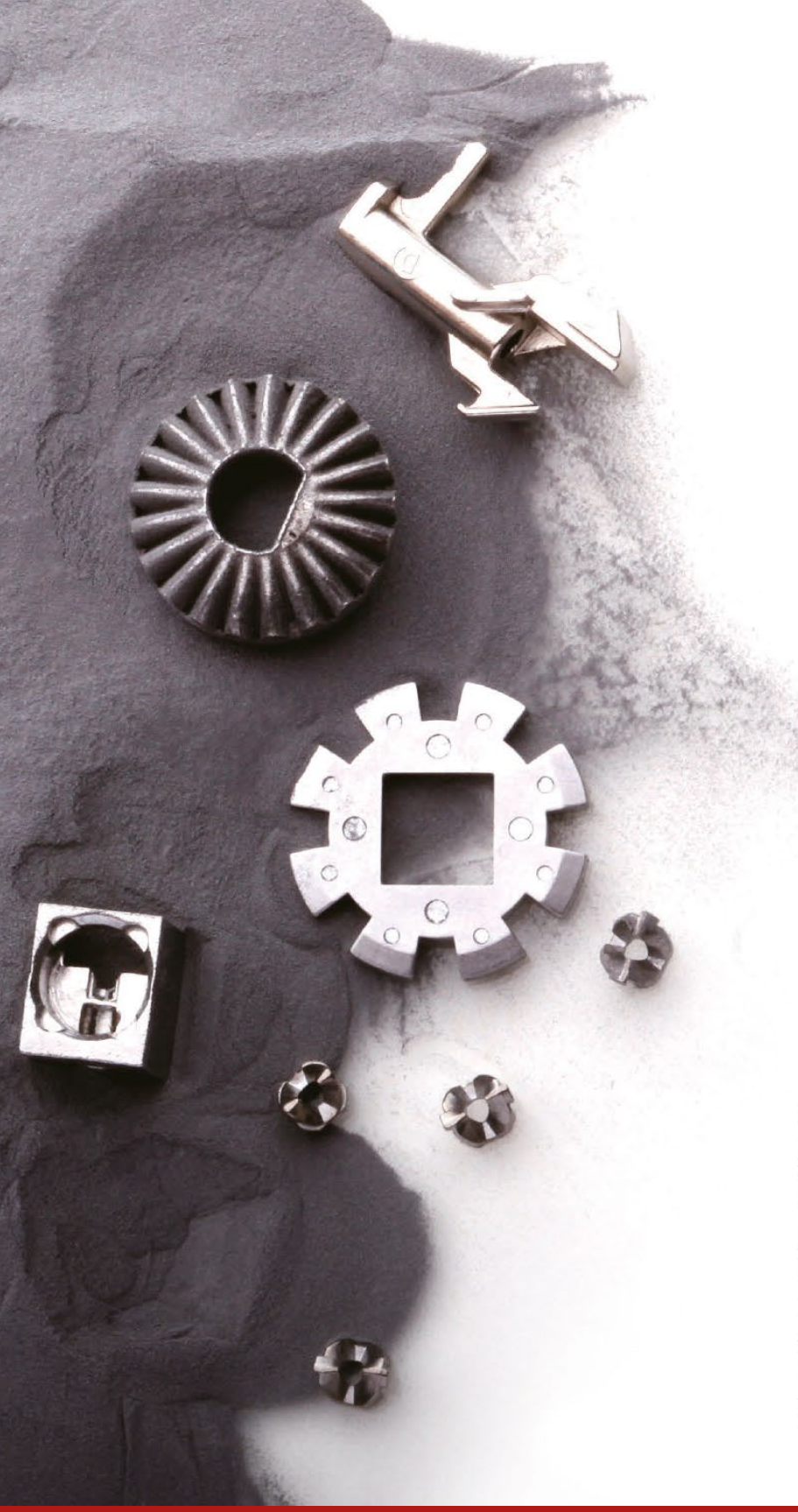
"Mantle far surpasses any additive metal technology that we have seen previously," stated Ray Coombs, president and founder of Westminster Tool. "The precision and quality we get off the printer allow us to bypass many of our internal manufacturing processes, which gives us an advantage in providing a better, faster product for our customers."

Hillary Thomas, Westminster Tool vice president, added, "There is a massive skills gap in the injection mould-making industry. Mantle's technology is so simple to use that, with minimal training, we can have someone operating and running this machine. Mantle will help Westminster Tool change how we do business."

Other beta customers include Fathom Manufacturing, one of North America's largest on-demand digital manufacturing platforms, which is reported to have reduced its toolmaking time by 45% with components made by Mantle's technology. Fathom reduced its toolmaking operations from 200 hours to 110 hours by eliminating or reducing several operations, including CNC milling, EDM and polishing.

Tessy Plastics, a global contract manufacturer specialising in injection moulding and custom automated assembly solutions, surpassed 1.25 million cycles on a production mould built with Mantle components. The mould, which makes deodorant packaging, contains both Mantle H13 and P2X tool steel components and is said to demonstrate the durability of Mantle's steels in a demanding production environment. Tessy Plastics achieved time savings of 60%, from 150 hours to 60 hours.

www.mantle3d.com



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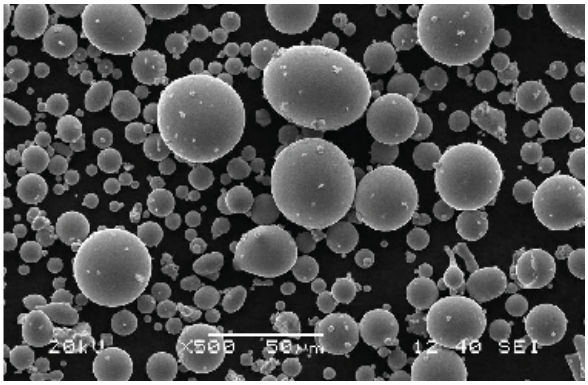

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Ultimaker announces Metal Expansion Kit for filament-based metal AM

Ultimaker, Utrecht, the Netherlands, a manufacturer of filament-based Material Extrusion (MEX) machines, has announced its Metal Expansion Kit which aims to make metal Additive Manufacturing more accessible and affordable. Users of the new kit will be able to produce components capable of high mechanical stress and thermal resistance, an achievement that would be impossible even with high-performance thermoplastics, states the company.

The Ultimaker Metal Expansion Kit has been developed to remove existing process bottlenecks and limitations by providing users with dedicated items, software features and knowledge to maximise process efficiency and further expand Ultimaker Additive Manufacturing machines capabilities beyond thermoplastics.

The kit includes materials that are automatically recognised by the machine's NFC sensor and enables efficient switching between processing plastic and metal. The technology is powered by Ultimaker Cura, the company's slicing software, and is compatible with the Ultimaker S5 machine.

"The Ultimaker Metal Expansion Kit is especially suitable for printing non-off-the-shelf parts such as tools, jigs and fixtures, replacement parts, functional prototypes and auxiliary components," stated Andrea Gasperini, Product Manager at Ultimaker. "The Kit provides access to a complete and validated 3D printing workflow on an open platform that offers competitive quality and lead times normally only accessible with full in-house metal Fused Filament Fabrication (MFFF) by solutions at a much higher total cost of ownership."

Ultimaker has introduced the Metal Expansion Kit, which aims to enable an accessible and affordable metal AM solution (Courtesy Ultimaker)

"Thanks to the low total cost of ownership and savings up to 90% over small series of not-standard auxiliary components and tools, our early adopters are already realising return-on-investment (ROI) in less than a year," he added.

www.ultimaker.com/metal

Mimete adds nitrogen atomisation option for custom metal powders

Mimete SrL, a division of the Fomas Group, Osnago, Italy, reports that its manufacturing facility can now offer nitrogen as well as argon for the atomisation of metal powders. The company states that due to the increased demand for custom metal powders, and the potential technical advantages nitrogen offers, the decision was made to expand the manufacturing facility's capacity.

According to Mimete, a number of new alloys specifically developed in partnership with its customers have revealed that manufacturing based on argon gas does not fulfil all the customer's technical requirements when compared with nitrogen gas.

Additionally, nitrogen gas is mandatory for some specific technologies and applications, as it provides the perfect chemical composition for the desired mechanical properties during the final stage. The manufacturing plant's lean design ensures, through a simple switch, a fully automatic changeover of the system, resulting in an elevated degree of efficiency and avoiding contamination.

In order to maintain the highest atomising performance, the vacuum inert gas atomisation (VIGA) system automatically manages the different physical properties between the two gases. Mimete atomisation recipes are custom-made in order to deliver the distinctive properties of each gas (for instance, nitrogen bears lower specific weight and higher cooling capacity) and to achieve the best metal powder characteristics.

As both gases are inert, they are able to reach very low levels of oxidation in the molten and powder forms. Therefore, they can be employed to equal effect in metal powder manufacturing. The company explains that argon is the gas of choice for manufacturing processes where high purity is required, such as nickel superalloys. Nitrogen is preferred in steel manufacturing dedicated to Hot Isostatic Pressing consolidation as it is soluble in metal.

Andrea Tarabiono, Manufacturing Director of Mimete, commented, "The addition of nitrogen, as an alternative to argon, integrates our starting plant set up, giving us the opportunity to fulfil the specifications of new customers and introduce brand-new alloys that were not feasible before. With a lean process, switching from one gas to the other is simple and straightforward. Moreover, it results in zero contamination between the two gases and enhances our market response."

www.mimete.com

Arburg reports positive response to its Technology Days 2022

Arburg's Technology Days were held from June 22-25 of this year, after a two-year break due to COVID-19. During the event, over 3,700 visitors came to the Arburg headquarters in Lossburg under the banner 'Think Tank'; on display were fifty machine exhibits, and the Efficiency Arena, with its focus on digitalisation and sustainability, service solutions and expert presentations.

"We are extremely proud of these incredible visitor numbers, because, after all, whole regions – for example, in Asia – were unable to travel due to Corona. Added to this is the fact that we organised the Technology Days four months before the world's leading trade fair, K, and not everybody will come to Europe twice within four months," stated Juliane Hehl, Managing Partner, Arburg. "The Technology Days certainly proved again their absolute global attraction. This makes it very clear to me that our customers and visitors could hardly wait for the Technology Days either!"

For the first time, sister companies AMKMotion and InnovatiQ also attended the conference with solutions for drive systems and Additive Manufacturing, respectively. A digital highlight was said to be the brand new 5G campus network. Presentations in the new training centre and exhibits and exhibition areas distributed across the entire company covered topics such as turnkey solutions, medical technology, Additive Manufacturing and servicing.

The Efficiency Arena was also said to have been met with a great response. Here, around twenty experts from Arburg and its partners provided information on all topics relating to arburgGREENworld and arburgXworld. The focus of the nine stations was on solutions for resource conservation and digitalisation along the entire injection moulding value chain. With the production of drinking cups that can be separated by type, the visitors were shown an application example of the R-Cycle initiative and learnt about the key topics of circular economy and digitalisation.

An overview of the entire range of products and services offered by Arburg in this respect was on display in two new, permanently installed rooms: in the arburgGREENworld, a hybrid Allrounder 370 H processed Post-Industrial Recyclate (PIR) that originated from technical textiles (airbags). For this purpose, the machine was equipped with Arburg's new 'recyclate' package. In the arburgXworld area, numerous options were shown for making production more efficient, transparent and sustainable thanks to digitalisation.

www.arburg.com

EPMA reelects president and treasurer during 35th General Assembly

The 35th General Assembly of the European Powder Metallurgy Association (EPMA) marked the first time in two years that members could meet at an in-person event, with the meeting taking place both online and in-person in Brussels, Belgium, on April 28, 2022. During the assembly, it was confirmed that EPMA President, Ralf Carlström of Hoganas AB and EPMA treasurer, Christoph Laumen, Linde GmbH, were re-elected to their positions for a further three-year term.

The EPMA team presented an overview of past and ongoing work. The current situation with the World PM2022 Congress was presented by Sabine Hazoume, while Romain Rayez gave an update on the Communication & Marketing activities. EPMA Technical Managers, Bruno Vicenzi and Kenan Boz, presented the various ongoing European projects and working groups, as well as an overview of the different Sectoral Groups activities over 2021/2022.

More detailed information was then reported by the chairmen of the various EPMA groups: Cesar Molins from Press & Sinter, Georg Breitenmoser from Metal Injection Moulding, Peter Kjeldsteen from Functional Materials, Steven Moseley from Hard Materials, Adeline Riou from Additive Manufacturing and Jim Shipley from Hot Isostatic Pressing.

Keynote speeches, presented towards the end of the assembly, saw Elena Vyboldina of Eurometaux discuss the Russia-Ukraine crisis and its impact on EU non-ferrous metals sector. Chris Heron presented 'Eurometaux on Legal Affairs' and Melina Hervet-Henry of AddUp Solutions gave a talk on 'Patents applications: a strategic value for the company.' A look at sustainability in the steel industry was also presented by Clare Broadbent, World Steel Association.

www.epma.com

Ralf Carlström, Hoganas AB, has been re-elected as EPMA President (Courtesy EPMA)

MIM at World PM2022: A focus on markets, sustainability and industry networking

The World PM2022 Congress & Exhibition, organised by the EPMA and taking place October 9–13, 2022, in Lyon, France, features thirteen Special Interest Seminars (SIS) which will highlight the diversity of metal powder manufacturing. Two of these seminars will focus specifically on Metal Injection Moulding.

MIM SIS: Sustainability of MIM
Session 56, taking place Wednesday 12 October, from 11:00–12:30 will be chaired by Georg Breitenmoser, Parmaco Metal Injection Molding AG, and Prof. Dr.-Ing. Frank Petzoldt, Fraunhofer Institut – IFAM.

Presentations will include:

- MIM & Green by Dr Jean-Claude Bihr (Alliance MIM)
- Sustainability of MIM in Japan by Kenji Doi (Osaka Yakin Kogyo)
- Discussion on MIM Sustainability Roadmap 2030 led by Georg Breitenmoser (Parmaco Injection Molding)

MIM SIS: Global MIM Market
Session 62, taking place Wednesday 12 October, from 14:30–16:00, will be chaired by Georg Breitenmoser, Parmaco Metal Injection Molding AG, and Prof. Dr.-Ing. Frank Petzoldt, Fraunhofer Institut – IFAM.

Presentations will include:

- European MIM Market by Dr Paul A. Davies (Sandvik)
- North American MIM market by Stefan Joens (Elnik Furnaces)
- Discussion on Trends in MIM Markets by Prof Dr Frank Peztoldt (Petzoldt Consulting)

EuroMIM
In addition to the MIM-focused seminars, World PM2022 will also hold the MIM Sectoral Group Meeting under the European Metal Injection Moulding Group (EuroMIM) which is scheduled to take place on Wednesday, October 12 from 17:00–18:30. EuroMIM was formed out of the successful three-year MIM Thematic Network "MIMNet" which finished in October 2000.

EuroMIM's objectives are to develop the potential and capabilities of MIM, to promote MIM to end users in particular to promote EuroMIM Group members' specialities and to provide a united European voice to the outside world.

MIM networking dinner
There will also be a MIM networking dinner organised by the EuroMIM EPMA Sectoral Group, with support from the German MIM Expertenkreis, which will take place on October 12. *PIM International* is a sponsor for this invite-only event.

www.worldpm2022.com

World PM2022 Congress & Exhibition will take place in Lyon, France, from October 9–13 (Courtesy EPMA)

Powder Injection Moulding virtual tutorial available from APMI International

APMI International, a professional society serving the needs of individuals working in the Powder Metallurgy industry, has announced the release of its Powder Injection Moulding virtual tutorial. Presented by Dr Randall M German, FAPMI, professor emeritus, San Diego State University, the self-study course is designed to provide a comprehensive foundation of the technology.

The course videos will be available to view for five days after purchase, and include an introduction to the manufacturing processes, feedstocks, moulding, debinding, sintering and finishing. A definition of what constitutes a viable PIM component, along with a comparison of PIM to competing technologies, is discussed. The course will also review the economic advantages of PIM.

Recorded in 2018, the four-part, six-hour course includes the following videos:

- Part 1: Introduction, Materials and Binders (two hours)
- Part 2: Injection Moulding, Debinding and Sintering (two hours)
- Part 3: PIM Part Design, Cost and Facilities (one hour)
- Part 4: Overview of PIM Markets and Opportunities (one hour)

Each registrant will also receive electronic copies of 'Metal Injection Molding – A Comprehensive MIM Design Guide', 'Injection Molding and Ceramics' and 'MPIF Standard 35-MIM 2018 Edition Materials Standards for Metal Injection Molded Parts'.

The course registration fee also includes a full-year of APMI International membership.

www.apmiinternational.org

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Ceramitec 2022 welcomes around 10,000 global visitors

The international ceramics trade fair ceramitec, which took place at Messe München on June 21–24, featured 356 exhibitors from thirty-four countries and attracted around 10,000 attendees from eighty-four countries.

Given the travel restrictions still in place for a number of countries, and geo-political uncertainties, the organisers were keen to highlight the trade fair's positive response. "We're very happy with how the trade fair went," stated Dr Jürgen Blumm, Managing Director of Netzsch-Gerätebau and chairman of the advisory board for ceramitec. "Naturally, the number of visitors was down, but we did have an above-average number of specific inquiries regarding short-term investment needs from companies all over the world. That's why Ceramitec 2022 is already a great success for us."

Hélder Almeida, Sales Manager at metalcértima, added, "The quality and international mix of specialist visitors was truly at a very high level. The people who were at our stand wanted to do business with us."

Karl Liedel, an authorised representative of Lingl Anlagenbau, explained, "Our expectations for Ceramitec 2022 were more than met. Many familiar faces stopped by the stand, but numerous new contacts were also made. Right now, it's vital that we talk about decarbonisation and help customers to save energy. That requires platforms like ceramitec, as they provide a place where experts can meet to discuss things. Last but not least, attending ceramitec confirmed for us that personal contact is more important than ever."

Mathilde Forestier, Communication and Events Director, Pôle Européen de la Céramique, which organised a joint stand with fifteen co-exhibitors and two trade forums in the conference program, emphasised, "Our presentations attracted large numbers of visitors. The people were well-versed and interested in what was on offer. Specifically, during the discussions afterwards, we often saw that solutions and innovations are also needed especially in processing many different materials and thermal processes in order to meet the current challenges."

Collin Davis, Executive Director of Capital Goods Shows at Messe München, stated, "I was delighted that the trade fair attracted so many specialist visitors from countries abroad. This proves how important ceramitec is on an international level. However, feedback from our exhibitors indicates very clearly that personal contact at trade fairs is essential. More than once, I heard people saying, 'Finally, we can meet in person again'."

The next ceramitec trade fair is scheduled to be held in Munich, Germany, April 23–26, 2024.

www.ceramitec.com

Lumafield announces $35M funding round for its industrial X-ray CT systems

Lumafield, a X-ray CT technology developer based in Cambridge, Massachusetts, USA, announced that it has closed a $35 million Series B funding round from new and existing investors, achieved a major new AI-driven performance breakthrough, and appointed two executives to its board of directors. To date, the company has raised a total of $67.5M.

When Lumafield emerged in April 2022, it offered what it called the world's first accessible industrial X-ray CT platform for a more affordable price than legacy systems. Now, the company has reputedly made its Neptune scanner over 300X faster, enabling scaling from one-off scans to serial inspection in high-volume manufacturing operations.

Behind the speed increase is a development in artificial intelligence. Lumafield's AI allows the company's reconstruction process to achieve the same results with fewer two-dimensional X-ray images, reducing the time required to run a scan.

New improvements in Lumafield's software also make it possible to skip certain steps in the reconstruction process before performing automated analysis, thus reducing process time. As a result, scans that previously took several hours are said to now run in a minute or less, making industrial CT a practical technology for quality assurance on factory floors. Combined with factory automation systems, Lumafield's scanner and software can inspect products at high volume, automatically flagging problems such as dimensional inaccuracies and the presence of pores and cracks.

Lumafield's industrial CT scanner with robotic arm for high volume inspection (Courtesy Lumafield)

"Industrial CT has been out of reach for most production lines – until now," stated Eduardo Torrealba, co-founder and CEO, Lumafield. "With these speed improvements and Lumafield's low price point, it's now possible to implement 100% inspection with CT, catching invisible issues before they become costly problems."

www.lumafield.com

Ceramic additive manufacturer Lithoz reports record first half 2022

Lithoz GmbH, headquartered in Vienna, Austria, announced that it has had a record first half year results in terms of order intake. By the end of the second quarter 2022, the company had already reached two-thirds of its full year order intake target. In light of this strong half year, the company forecasts that 2022 will be another successful year for Lithoz and the ceramic Additive Manufacturing industry.

Now in its eleventh year, Lithoz was founded as a spin-off from the TU Wien by Dr Johannes Benedikt and Dr Johannes Homa. Since then, the company has grown to offer a range of industry-trusted ceramic Additive Manufacturing machines for various applications, including medical, dental and industrial. Lithoz has also developed ceramic AM materials to suit different requirements.

"This continuous strong order intake shows that it has been another year of success thanks to lots of hard work and cooperation – not only within our own team, but also with our partners and customers," stated Homa, Lithoz CEO. "We can already see our vision of establishing ceramic 3D printing as a powerful manufacturing technique for every application becoming reality!"

The company uses a Vat Photopolymerisation (VPP) process, which it calls Lithography-based Ceramic Manufacturing (LCM), in combination with Digital Light Processing (DLP), to form three-dimensional objects layer-by-layer by the selective photopolymerisation of a ceramic-loaded liquid formulation, or slurry. Once built, the green parts have to be debound and sintered according to the requirements of the material used. Following this thermal stage, theoretical densities above 99.8% are achieved and a homogeneous microstructure is developed.

www.lithoz.com

Lithoz's CeraFab Multi 2M30 machine uses a Vat Photopolymerisation process which the company calls Lithography-based Ceramic Manufacturing (Courtesy Lithoz)

Ceramic Injection Moulding used to produce microfluidic chips

Microfluidic devices have gained tremendous interest in both academic and industrial research due to key advantages such as fast response times and low analytic consumption. The manufacture of first generation microfluidic chips involved silicon but, to date, numerous materials (e.g., quartz/fused silica, glass, ceramics, polymers and metals) have been used depending on the diverse functionalities of the various microfluidic devices.

Currently, some microfluidic applications are integrated with infrared (IR) spectroscopy, which is used to measure the bond vibration frequency in a molecule and determine the functional group. Most polymeric and glassy substrates used in microfluidics chips are, however, not transparent in the mid-infrared region, and normal IR-compatible materials are expensive and challenging for micro-fabrication. Transparent polycrystalline ceramics can solve the problems of transparency and have the potential to be used in microfluidics applications coupled with FTIR analysis, providing that the required microfeatures can be manufactured in the ceramic substrates at low cost.

A joint research programme at the Singapore Institute of Manufacturing Technology (SIMTech), School of Mechanical and Aerospace Engineering, Nanyang Technological University (NTU), and the Institute of Chemical and Engineering Science (ICES), all based in Singapore, has shown that Ceramic Injection Moulding can successfully be used to produce net or near-net shape high performance IR transparent ceramic microchips with small complex micro features as fine as 100 µm at a relatively low cost. The results of the research outlining the feasibility to produce IR transparent ceramic microfluidic chips with the desired feature profiles, microstructures and optical properties by PIM have been published as a Short Communication by Tao Li, *et al.*, in *Research & Development in Materials Science*, July 7, 2021, 1707-1712.

The authors of the communication reported that high-purity yttria (Y_2O_3) powder having an average particle size of 0.25 µm was spray dried to produce spherical particles of 30–50 µm. 5 mol.%3Y-zirconia powder was added to batches of the yttria powder by ball milling in order to reduce the sintering temperature and further improve transparency. To this mixture was then added an in-house developed binder system based on paraffin wax (PW), polypropylene (PP) and stearic acid (SA) to produce the CIM feedstock.

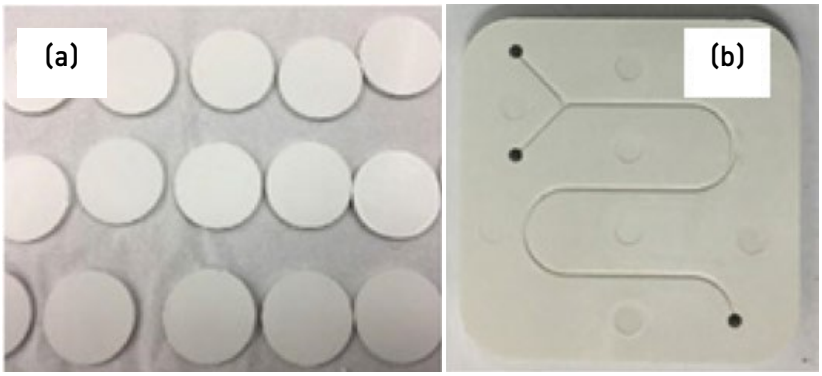

Fig. 1 Green parts of (a) circular discs and (b) square microfluidic chips (From paper: 'IR Transparent ceramic microfluidic chips produced by Powder Injection Moulding', by Tao Li, et al., Research & Development in Materials Science, July 2021, 1707-1712)

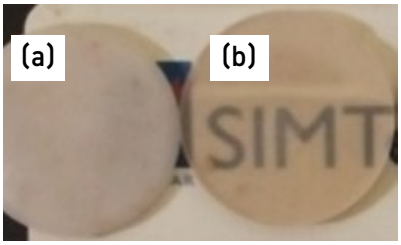

Fig. 2 As-sintered yttria discs (a) without and (b) with zirconia addition (From paper: 'IR Transparent ceramic microfluidic chips produced by Powder Injection Moulding', by Tao Li, et al., Research & Development in Materials Science, July 2021, 1707-1712)

After optimising the injection moulding parameters, circular discs of 20 x 2 mm and square microfluidic chips of 25 x 25 x 2.5 mm with micro-channels of 200 µm width and depth of 100 µm were produced as shown in Fig. 1. Solvent debinding was used to remove most of the PW and SA binders from the moulded green parts. The remaining binder was removed in a multi-stage thermal debinding process, in which the parts were heated up in an inert atmosphere and strictly controlled heating profile. After thermal debinding, the brown parts were transferred to a high vacuum furnace for sintering at temperature of 1770°C and different dwell times.

Fig. 3 Polished yttria ceramic disc (From paper: 'IR Transparent ceramic microfluidic chips produced by Powder Injection Moulding', by Tao Li, et al., Research & Development in Materials Science, July 2021, 1707-1712)

As mentioned earlier, the addition of zirconia plays an important role in manufacturing transparent yttria. PIM discs with and without zirconia sintered at 1750°C are shown in Fig. 2 and it is clear that the as-sintered sample without zirconia addition (Fig. 2a) is still opaque whilst a certain transparency has been achieved with zirconia addition (Fig. 2b).

Polishing the yttria disc sample containing zirconia gives an even better transparency compared with the as-sintered part (Fig. 3). Light transmittance in the polished PIM discs is also increased by around 10–20% compared with the unpolished samples. The researchers stated that this is due to less light being scattered at the polished surface compared to that of the unpolished surface. For the parts after polishing, the transmittance is around 50—70% in the visible light range (400—800 nm). The transmittances increase from short wavelength to long wavelength and the sample has a transmittance of 70—74% at the infrared wavelength. Compared with yttria single crystal, which has a transmittance around 80% in the same wavelength range, 90% of transmittance can be achieved in the polycrystalline ceramic produced by Powder Injection Moulding.

The micro-channels in the sintered ceramic microfluidic chips were found not to dramatically affect transparency. Fig. 4 shows the top view and cross section of the channel under optical microscope with width of around 250 µm and depth of around 90 µm.

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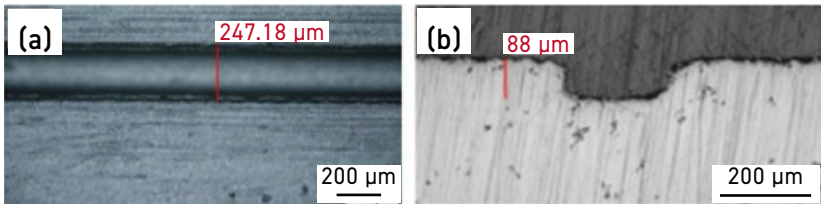

Fig. 4 Micro-channel in the sintered chip from (a) top view and (b) cross section (From paper: 'IR Transparent ceramic microfluidic chips produced by Powder Injection Moulding', by Tao Li, et al., Research & Development in Materials Science, July 2021, 1707-1712)

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Overview of producing highly porous titanium using the MIM/Space Holder process

In a comprehensive review by a group of researchers at Federal University of Santa Catarina (UFSC), Brazil, the Universidad Técnica Federico Santa María, Chile, and the Santa Cruz State University (UESC), Brazil, recent advances in the processing of titanium via Metal Injection Moulding combined with the space holder method are presented. This manufacturing approach can be used to obtain porous medical implants which have high biocompatibility with the human body at the microstructural, chemical, and mechanical level. The twenty-one page review with ninety-nine references was published online in the journal *Metals* on April 30, 2022, with the lead author being Francisco Cavilha Neto at UFSC.

The review first focuses on the significant growth in the global demand for biomaterials which have emerged over the past two decades, and which provide excellent biocompatibility when used as biomimetic implants. The authors state that, in addition to good biocompatibility, biomaterials must also meet the following requirements: suitable mechanical properties (modulus of elasticity, yield strength, fatigue strength, wear and corrosion resistance) and a certain level of porosity to allow for osseointegration of bone into the implant. By definition, biocompatibility is a material's ability to perform as a good 'guest' in a given application environment that requires interaction. The biological response is the local and systemic response of the host organism to the implanted biomaterial.

One of the main difficulties in achieving a very high degree of osseointegration is related to the difference between the elastic modulus of the implant material and the underlying bone structure. This can be overcome by the use of porous components manufactured using processes such as Metal Injection Moulding combined with the space holder (SH) method, powder compaction, and Additive Manufacturing (see Table 1). The pores generated from these processing methods, in addition to reducing the elastic modulus of the implant, provide the adherent surface necessary for cell proliferation and adhesion, thus avoiding the stress shielding effect. Furthermore, bone growth into the implant is determined by the porosity, pore size, and structure, allowing adequate vascularisation of cells and fluids. Good control over the required level of porosity

Method	Advantages	Disadvantages
Conventional powder compaction with space holder (PC–SH)	• High level of porosity (60–80%), with adequate mechanical strength • Easy to industrialise, less expensive, as well as less time consuming than prototyping techniques (such as Additive Manufacturing) • Less waste of materials	• Randomness of the process and type of SH particle could produce a variation in wall thickness and interconnection size that can deteriorate its mechanical performance • High plastic deformation - Geometry limitation
Metal Additive Manufacturing	• Less waste • High geometrical freedom • High precision components • Moderate energy costs • Rapid prototyping and on-site repair	• Expensive equipment • More time-consuming • Molten pool instabilities and higher residual stresses • Higher probability of contamination (for laser-based Additive Manufacturing) • Unpredictable properties due to melting and thermal history
Metal Injection Moulding (MIM–SH)	• Capable of producing both porous and dense small parts • High design flexibility • Large-scale production • Free geometry and design • Low cost	• Reduced part size • Higher initial cost than PC–SH • A quantity of material is removed during processing • 15–20% linear shrinkage during processing

Table 1 Comparison of the different techniques for processing highly porous Ti implants (From paper: 'An Overview of Highly Porous Titanium Processed via Metal Injection Molding in Combination with the Space Holder Method', by F C Neto, et al., Metals, 12/2022, 783, 21 pages)

Material	Particle Size	Removal	Observation	References
Sodium Chloride (NaCl)	200–500 µm	Aqueous solution 50–60°C for 40 to 72 h	• Good water solubility and low cost • High melting point	[22,28,67]
Potassium Chloride (KCl)	250–500 µm	Aqueous solution 50–60°C for 24 to 72 h or thermal removal at 750°C for 2 h	• High solubility in water, available in multiple shapes • Lower melting point	[27–29]
Polymethylmethacrylate (PMMA)	D50 = 600 µm	Thermal 200–450°C for 2 h	• Control of the macropore morphology • Can be used as a binder • May contaminate the powder with C and O	[22,68]
Magnesium	300–1500 µm	Thermal during sintering	• Can be leached with solvents	[69]
Ammonium bicarbonate NH_4HCO_3	500–800 µm	Thermal 175°C	• May contaminate the powder with interstitial elements • Easy and complete removable due to moderate decomposition temperature	[26,70]
Tapioca Starch	100–400 µm	Aqueous solution or in a furnace at 450°C	• Low cost • Easy access • Easy removal	[71]

Table 2 Typical space holder materials cited in the literature and their morphologies and removal characteristics (From paper: 'An Overview of Highly Porous Titanium Processed via Metal Injection Molding in Combination with the Space Holder Method', by F C Neto, et al., Metals, 12/2022, 783, 21 pages)

must, therefore, be performed in order to achieve a precise balance between the mechanical properties and the biological and adhesion performance of the implant.

Several researchers are already reported to have applied the combination of MIM and SH to produce titanium foams with elastic modulus values close to those of bone, and pore percentages in the range of 30% to 72%. In this context, the authors of this review focus on the published advances made in processing foams using MIM combined with the space holder method for producing highly porous Ti implants. The suitability of different types of Ti powders, typical space holder materials (Table 2), plus processing parameters for feedstock preparation, injection moulding, binders and debinding and the removal of the space holder material, and, finally, sintering, are discussed in detail based on the authors' experience to overcome problems that may affect the integrity of the final component, for example, those related to porosity, contamination, dimensional accuracy, and mechanical properties. Table 3 gives a summary of MIM/SH feedstock configurations found in the literature including some process and property data.

The authors stated that whilst there is currently still no commercial production of porous Ti implants for medical applications using MIM technology combined with the space holder method, they hope that their comprehensive overview will increase awareness regarding this promising technology among both

researchers and MIM manufacturers. They highlight some of the new patents aimed at optimising the MIM route for producing porous Ti-based biomaterials, and conclude that to achieve the potential for this promising manufacturing route, the high cost of the initial Ti powder – which, ideally, should be a very fine powder with spherical particles – must be addressed. In this regard, studies underway on the use of low-cost HDH and TiH_2 powders are promising, aimed at reducing the processing costs.

The problems concerning Ti powder shape and contamination are also under investigation to enhance the potential for the use of these powders by applying a protective atmosphere and/or plasma treatment. In addition, research on the control of process-induced contamination is being undertaken in terms of exploring, for instance, the use of hydrogen in the sintering process to reduce the oxygen content in the final porous sintered body. Finally, studies to address the problem of dimensional stability are being conducted. Plasma sintering may provide an important tool for achieving dimensional stability and, at the same time, assist in the removal of binders. under a controlled atmosphere.

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Ref.	Ti powder	Solid loading Ti+SH (vol.%)	Space holder (vol.%)	SH grain size (μm)	Binder (vol.%)	Sintering temperature and time	Porosity after sintering (vol.%)	Young's Modulus (GPa)
Morelli *et al.* [22]	Angular HDH D50 = 20.26 μm	50–60	50	300–500	50–40	1000°C for 4 h	59–51	6–12
Zheng *et al.* [23]	HDH < 77 μm	55	30–40–50	< 290	45	1150°C for 2 h	42–45–62	3.0–1.5–1.1
Daudt *et al.* [27]	Spherical gas-atomised < 32.8 μm	80	70	355–500	20	1200°C for 3 h	64	N/A
Laptev *et al.* [29]	Spherical gas-atomised D50 = 19.1 μm	72–75–80	70	355–500	28–25–20	1200°C for 3 h	59–61–55	8.6–7.4–10.3
Shbeh *et al.* [30]	Spherical gas-atomised < 74.9 μm	58	0–17–35–52–60	D50 = 366	42	1320°C for 2 h	20–44–56–62–65	N/A
Özbilen *et al.* [67]	Irregular HDH D50 = 48.3 μm	68	70	100–500	32	1300°C for 3 h	61	N/A
(N/A = not applicable)								

Table 3 summary of MIM feedstock configurations found in the literature (From paper: 'An Overview of Highly Porous Titanium Processed via Metal Injection Molding in Combination with the Space Holder Method', by F C Neto, et al., Metals, 12/2022, 783, 21 pages)

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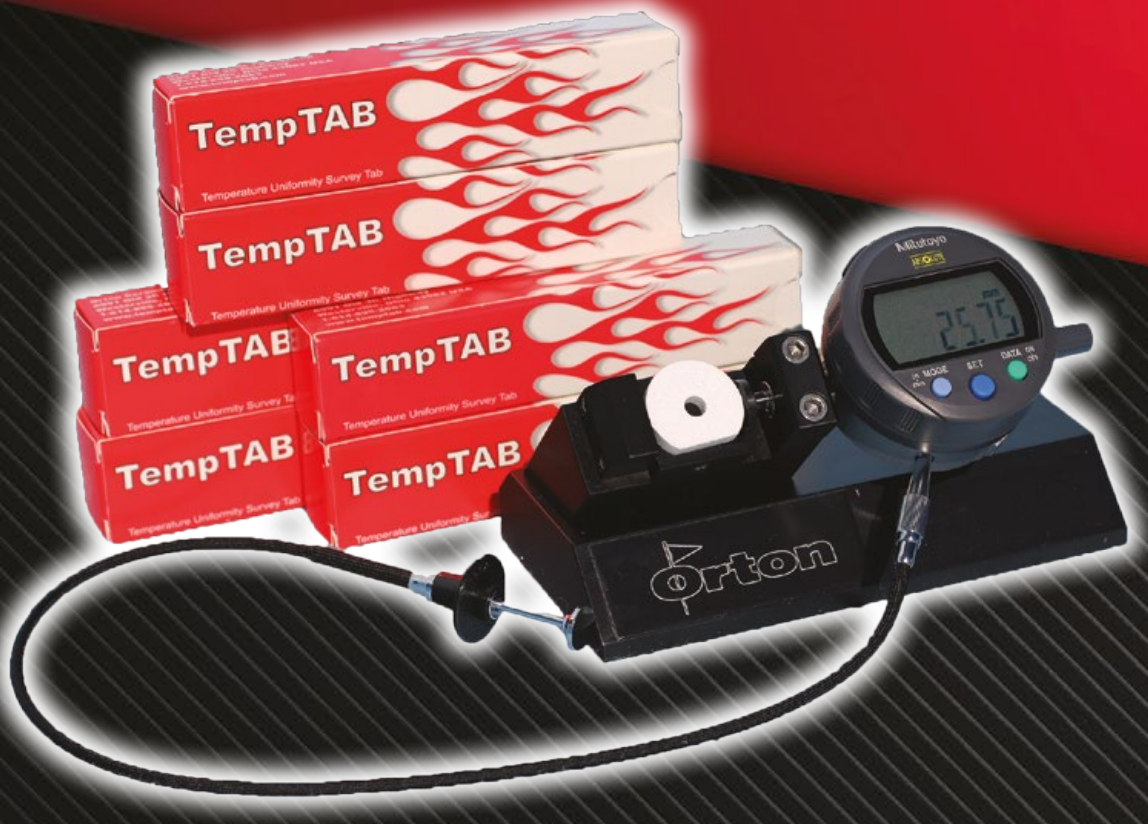

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Biocompatibility of 316L stainless steel vascular stents made by Metal Injection Moulding

Vascular stents are specially designed hollow metal mesh tubes that are inserted into a collapsed blood vessel via a catheter and permanently support the vessel's walls to prevent another closure. They are reported to have excellent therapeutic effect and have a high rate of success in treating coronary and peripheral artery disease. Currently, stents made by braiding or laser cutting techniques occupy most of the market share, but these techniques have certain disadvantages such as the high cost of equipment, high production costs, and poor geometric properties such as more nodes on the surface and a greater metal surface area, which can significantly increase the risk of thrombosis and restenosis rate after stent implantation.

Lower cost near net-shape processes are being explored for biodegradable stent materials but to date there have been very few reports on production of stents using Metal Injection Moulding (MIM) (see *PIM International* Vol. 6, No. 4, December 2012).

More recently, researchers at the Departments of Vascular Surgery, Second Xiangya Hospital, Central South University (Changsha), and the Department of Vascular Surgery, Fuwai Hospital (Beijing), in conjunction with the State Key Laboratory of Powder Metallurgy, Central South University, (Changsha), and the School of Microelectronic and Materials Engineering, Guangxi University of Science and Technology (Liuzhou), all based in China, have been studying the use of MIM to produce stent scaffolds using 316L stainless steel powder.

The MIM 316L stents were implanted into the iliac arteries of adult dogs using a standard angioplasty technique. The MIM processing parameters, stent properties, status of experimental animals, and endothelialisation of implanted stents were investigated, and a molecular biology evaluation was carried out. The results of their investigation were published in the paoer: 'Biocompatibility of vascular stents manufactured using Metal Injection Moulding in animal experiments' by Chang Shu, *et al.* in the *Transactions of Nonferrous Metals Society of China* Vol. 32, 2022, 569-580.

The authors reported that the gas atomised 316L stainless steel powder used in this study had a D_{50} = 12.5 µm particle size, and that this was mixed with a multicomponent binder comprising paraffin wax and low-density polyethylene (LDPE). In order to study the effect of carbon content fluctuations on the mechanical and

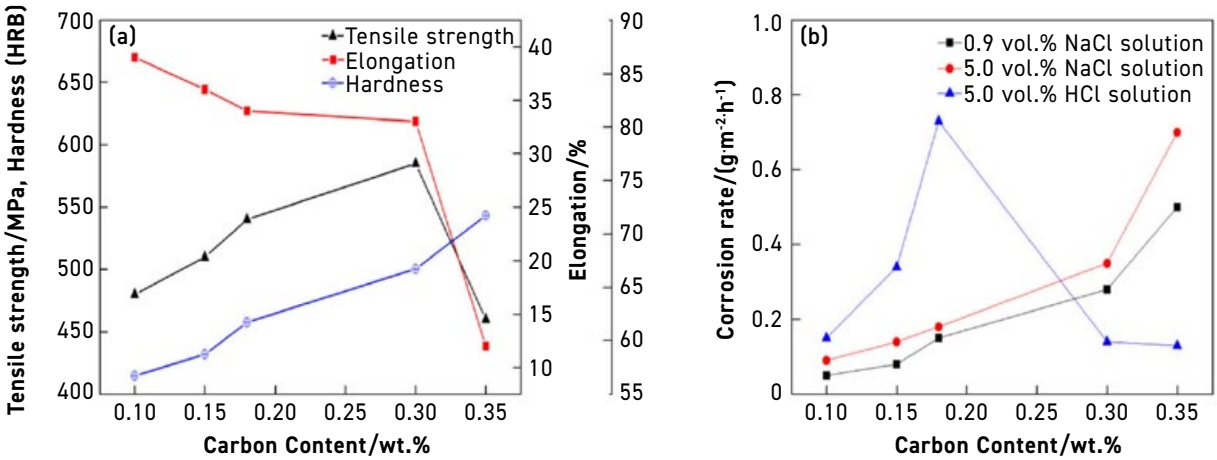

Fig. 1 Mechanical properties (a) and corrosion rate (b) of MIM 316L stainless steel with different carbon contents. (From paper: 'Biocompatibility of vascular stents manufactured using metal injection moulding in animal experiments' by Chang Shu, et al., Transactions of Nonferrous Metals Society of China, Vol. 32, 2022, 569-580)

corrosion properties of the sintered MIM 316L stainless steel, the authors added 0-0.4 wt.% graphite. Injection moulded tensile test specimens were subject to solvent debinding and thermal debinding followed by sintering at 1340°C and 0.1 Pa.

Results of the testing for tensile strength, elongation and hardness of the sintered 316L MIM samples with different carbon contents are shown in Fig. 1(a). It was found that increasing the carbon content from 0.1 wt.% to 0.30 wt.% saw an increase in the tensile strength from 480 to 585 MPa, which then decreased to 460 MPa at a carbon content of 0.35 wt.%. The hardness of the sintered sample increased with increasing carbon content, while the elongation decreased, particularly when the carbon exceeded 0.30 wt.%.

Corrosion testing of the MIM 316L stainless steel was done in different solutions (NaCl and HCl) (Fig. 1(b)). The corrosion resistance was found to decrease with increasing carbon content, particularly in the NaCl solution, with the corrosion rate increasing when carbon content exceeded 0.3 wt%. Nevertheless, the corrosion resistance of the MIM 316L stainless steel stents with a carbon content below 0.2 wt.% was found to be acceptable. The authors stated that carbon combines with Cr to form carbide, which degrades the Cr content in the 316L stainless steel matrix and hence accelerates corrosion. In HCl solution, the corrosion

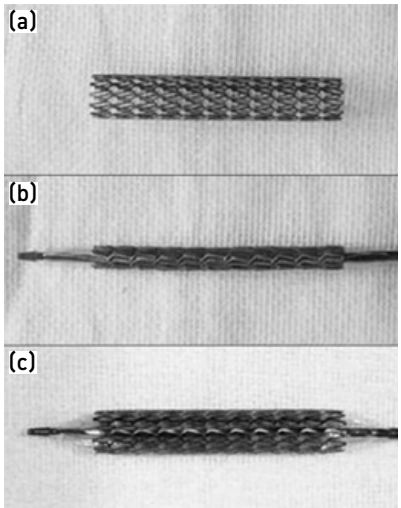

Fig. 2 MIM 316L stainless steel vascular stents in as-received (a), folded (b), and expanded (c) states (From paper: 'Biocompatibility of vascular stents manufactured using metal injection moulding in animal experiments' by Chang Shu, et al., Transactions of Nonferrous Metals Society of China, Vol. 32, 2022, 569-580)

rate is considerably higher than that in NaCl solution when the carbon content is not greater than 0.2 wt.%. However, beyond this, the corrosion rate in HCl solution is lower than that in NaCl solution. The authors plan further investigations to elucidate this mechanism. They also stated that because mechanical properties and corrosion resistance of 316L stainless steel are extremely sensitive to the fluctuation in the carbon content, this needs to be precisely controlled to satisfy the performance requirements of MIM vascular stents.

The authors used 316L stainless steel stents with ultra low carbon content having good corrosion resistance to produce the actual MIM stents shown in Fig. 2, which were used in in-vitro toxicity and in-vivo reliability studies. The as-received MIM stents exhibited good shape retention with no nodes, stains, cracks, or other defects on the surface. Some of the residual 316L stainless steel powder observed on the side surfaces of the stents (as can be seen in Fig. 3 (e) and (f)) were removed by an electrical polishing process.

The MIM vascular stents showed a completely austenitic structure with grain sizes ranging from 20–100 μm. The composition and size of the grains on the outer layer were similar to those in the centre, which indicated that MIM technology could produce a completely homogenous microstructure.

In-vitro cytotoxicity testing to evaluate the safety of the MIM 316L stainless steel stents showed no obvious cell toxicity and the MIM stents were successfully implanted into the aortas of dogs. In-vivo biomedical behaviour of the MIM vascular stents using digital subtraction angiography (DSA) showed that no migration, twisting, collapse, infection, acute or chronic thrombosis, stenosis or obstruction of the stents was observed during the entire observation period of up to six months. The results implied that the MIM stents showed good performance and biocompatibility; however, the authors stated that longer observation periods were still warranted. The authors concluded that compared with laser cutting and braiding, MIM technology considerably improves the utilisation of stent materials. To the best of their knowledge, this study is the first to validate the biocompatibility and safety of MIM vascular stents in experimental animals. However, they recommend that further studies be carried out in other material systems, as well as an investigation into mechanical fatigue reliability and biological safety.

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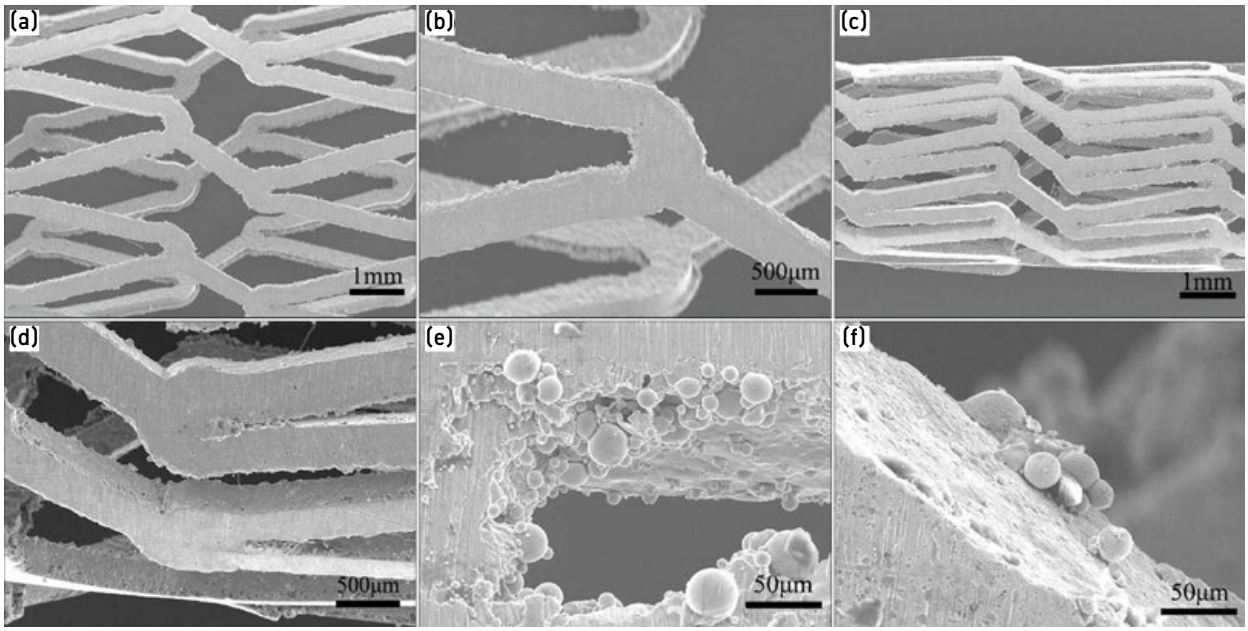

Fig. 3 SEM images of MIM 316L stainless steel vascular stents in expanded (a, b), and folded (c, d) states, and powder particles affiliated to stents (e, f) (From paper: 'Biocompatibility of vascular stents manufactured using metal injection moulding in animal experiments' by Chang Shu, et al., Transactions of Nonferrous Metals Society of China, Vol. 32, 2022, 569-580)

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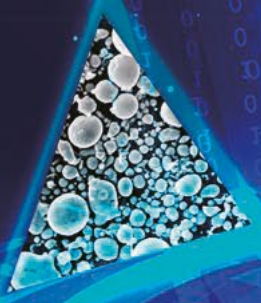

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Investigation of static and dynamic properties of MIM β titanium alloys

Metastable β titanium alloys offer a combination of excellent biocompatibility and mechanical properties, particularly toughness and fatigue, and, as such, find extensive applications in both the lightweight structural and biomedical fields. In addition, β titanium alloys can be engineered to allow for tuning the chemical composition of non-toxic alloying elements in such a way that low Young's modulus, as well as good biocompatibility, can be achieved. However, β titanium alloys produced by binder-based powder technologies, such as Metal Injection Moulding, can generally have more processing-related defects than those of the more common α/β type Ti-6Al-4V alloys made by non-binder powder metallurgy processes. These defects in as-sintered β Ti-parts include: residual porosity, high impurity levels, and coarse-grained microstructures.

A joint research project undertaken by Northwest Institute for Non-ferrous Metal Research, Xi'an, China, and the Helmholtz-Zentrum Hereon, Geesthacht, Germany, set out to study, in the light of existing literature, the influence of the above mentioned defects on the damage tolerances of MIM β titanium alloys under static and dynamic loading. The results of this research have been published in a paper by the authors Peng Xu, *et al*, in *Powder Metallurgy* journal. The authors focused on two metastable β titanium alloys: Ti-20Nb-10Zr alloy (TNZ) and Ti-20Nb10Zr-0.1Y alloy (TNZY), which were correspondingly blended from the starting powders shown in Table 1. Injection moulded green parts were dog-bone shaped with a length of 90 mm for tensile testing and rectangular shaped (50 x 6.3 x 3.4 mm) for fatigue testing.

The moulded green parts were first immersed in n-hexane at 40°C for 15 h for debinding, and the (brown) parts were subsequently placed in a vacuum furnace for conventional thermal debinding (argon flow under 600°C at a constant gas pressure). This was followed by high vacuum sintering (at ca. 10^{-5} mbar and 1400–1500°C for 4 h with a set cooling rate of 10°C min^{-1}). The authors stated that the oxygen levels of some as-sintered parts were roughly adjusted by a special heat treatment in mixed argon-oxygen gas at 500°C for different dwell times before final sintering after the pre-sintering stage (700°C/1 h). The carbon levels of some as-sintered parts were increased significantly to generate high carbon contamination by using a comparably 'dirty' retort without any burn-out clean-up programmes in advance. Finally, shot peening finishing was applied to the fatigue testing MIM parts to create compressive stress in an approximately 100–200 μm surface layer in order to erase surface defects such as open surface porosity.

The microstructures of the metastable β titanium TNZ and TNZY alloys were investigated, and the authors found a number of Y_2O_3 particles adjacent to porosity in the TNZY alloy (Fig.1(b)), and also that the coarse β grains contain differently oriented secondary α platelets as shown in Fig. 1(c). Residual porosity in the as-sintered β titanium alloy samples was found to be much higher (approx. 3-6%) compared to the porosity of as-sintered Ti6Al4V (2–3%). The porosity distribution of the investigated metastable β TNZ and TNZY alloys can also be seen in Fig. 1.

The authors stated that oxygen and carbon are the interstitial impurities which significantly influence the mechanical properties of MIM titanium alloys. They further stated that the current consensus is that the impurity contamination is mainly generated during the sintering process, partially from starting materials, and also from debinding processes. They reported that oxygen atoms in the interstitial solid solution state are able to affect the fracture mechanisms of (β) titanium alloys. However, for carbon atoms, once their content exceeds 60–230 μg/g (carbon solubility in β titanium alloys), carbon-deficient titanium-carbide (TiCx) precipitates. They are often located along prior β grain boundaries (GB) and

Powder	Particle shape	Particle size [μm]	Supplier	Grade	Carbon level [μg/g]	Oxygen level [μg/g]
Ti elemental	Spherical	< 45	TLS Technik Germany	Grade 1	60	1250
Ti-42Nb master-alloyed	Spherical	< 45	H.C. Starck Germany	N/A	63	3103
Ti-42Nb master-alloyed	Spherical	< 63	H.C. Starck Germany	N/A	37	2674
Zr elemental	Spherical	< 45	Alfa Aesar USA	N/A	142	5075
Zr elemental	Irregular	< 45	abcr Germany	N/A	N/A	N/A
Y elemental	Irregular	< 45	Edgetech Industries USA	N/A	390	9930

Table 1 Metallic powders used in the present metastable β titanium alloys (From paper: 'Influence of defects on damage tolerance of Metal Injection Molded β titanium alloys under static and dynamic loading', by Peng Xu, et al., Powder Metallurgy, published online, 6 May, 2022, 12 pages)

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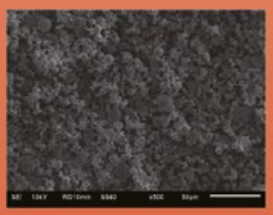
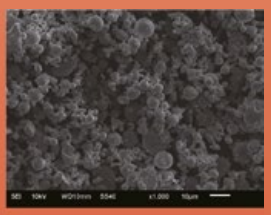
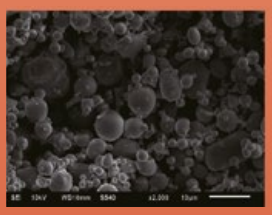
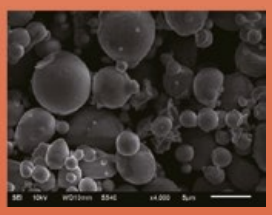
Item	T.D(g/cm^3)	S.S.A(m^2/g)	S.D(g/cm^3)
316L	4.8	0.34	7.9
17-4PH	4.7	0.34	7.7
304L	4.8	0.34	7.8
HK30	4.7	0.34	7.7
4J29	4.9	0.34	7.95
F75	5.0	0.34	8.1

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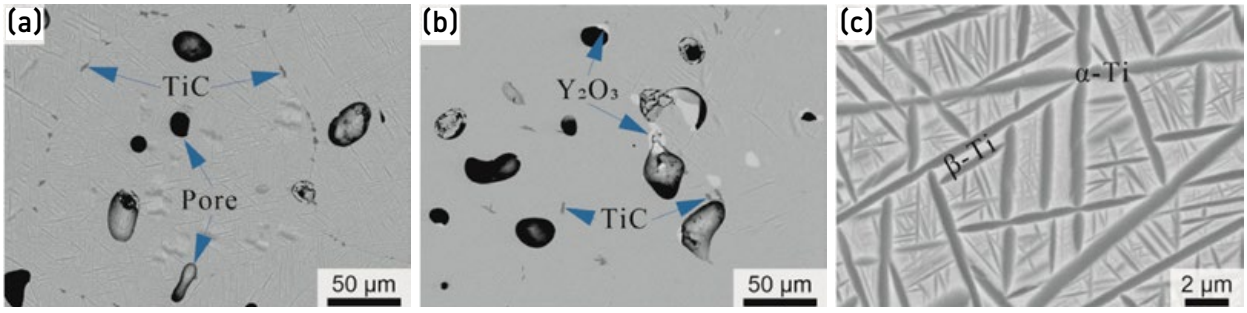

Fig. 1 Microstructures of MIM metastable β titanium alloys (a) β TNZ alloy; (b) β TNZY alloy; and (c) internal microstructure of β grain of TNZ alloy (TNZY is similar) (From paper: 'Influence of defects on damage tolerance of Metal Injection Molded β titanium alloys under static and dynamic loading', by Peng Xu, et al., Powder Metallurgy, published online, 6 May, 2022, 12 pages)

Process parameter		Alloy	Oxygen level [μg/g]	Carbon level [μg/g]	Carbide fraction [area%]
< 63 μm Ti-42Nb powder, *ca.* 35 vol.% binder	Clean sintering	β TNZ	2650	470	0.53
	Clean sintering	β TNZY	2490	530	0.48
< 45 μm Ti-42Nb powder, *ca.* 33 vol.% binder	Clean sintering	β TNZ	3775	597	0.55
	Polluted sintering	β TNZ	3893	1670	2.14

Table 2 Impurity levels and carbide fraction of metastable β titanium alloys (From paper: 'Influence of defects on damage tolerance of Metal Injection Molded β titanium alloys under static and dynamic loading', by Peng Xu, et al., Powder Metallurgy, published online, 6 May, 2022, 12 pages)

seriously deteriorate the crack resistance (or damage tolerance) of β titanium alloys. The impurity levels and carbide fractions of investigated β TNZ and TNZY alloys produced in this research by using different processing parameters are listed in Table 2.

The authors investigated how the sintering temperature affected damage tolerance (i.e. a combination of strength and elongation to fracture) under static loading, and they also elaborated on the effects of oxygen solutes, carbide precipitates and secondary α precipitate (αs) coarsening behaviour on crack resistance of MIM β titanium alloys. The

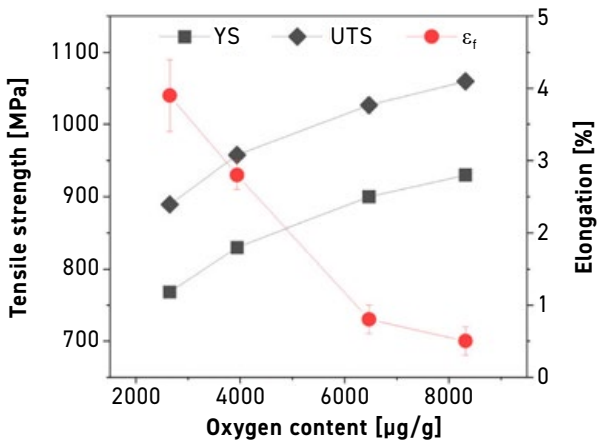

Fig. 2 Tensile properties of MIM metastable β TNZ alloys with varying oxygen contents (From paper: 'Influence of defects on damage tolerance of Metal Injection Molded β titanium alloys under static and dynamic loading', by Peng Xu, et al. Powder Metallurgy, published online 6 May, 2022, 12 pages)

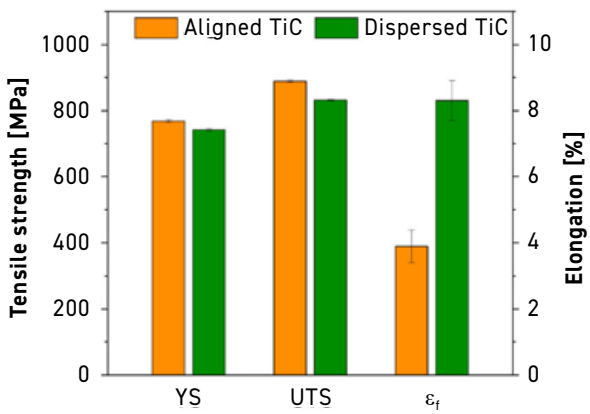

Fig. 3 Tensile properties of MIM metastable β TNZ(Y) alloys with either the aligned GB-TiC or the dispersed intragranular TiC (From paper: 'Influence of defects on damage tolerance of Metal Injection Molded β titanium alloys under static and dynamic loading', by Peng Xu, et al. Powder Metallurgy, published online 6 May, 2022, 12 pages)

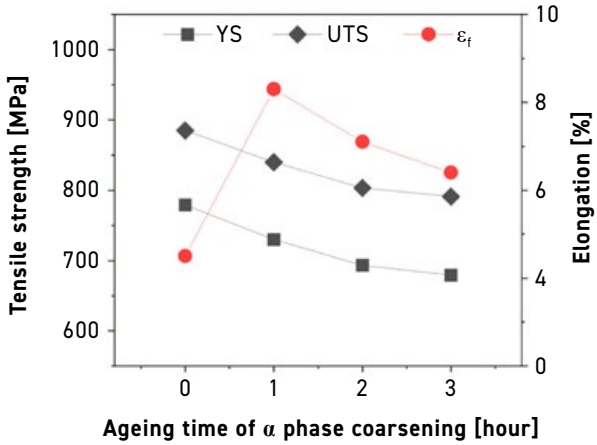

Fig. 4 Tensile properties of MIM metastable β TNZY alloys annealed at 800°C for different holding times to coarsen secondary precipitates (From paper: 'Influence of defects on damage tolerance of Metal Injection Molded β titanium alloys under static and dynamic loading', by Peng Xu, et al. Powder Metallurgy, published online 6 May, 2022, 12 pages)

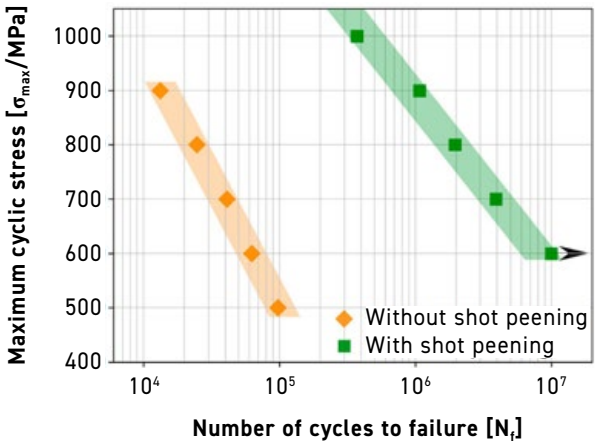

Fig. 5 Fatigue performance of MIM metastable β TNZ alloys with/without shot peening (From paper: 'Influence of defects on damage tolerance of Metal Injection Molded β titanium alloys under static and dynamic loading', by Peng Xu, et al. Powder Metallurgy, published online 6 May, 2022, 12 pages)

tensile properties of sintered β TNZ alloys with varying oxygen contents obtained by independent oxidisation treatments are shown in Fig. 2. The authors stated that it seemed plausible to increase the oxygen limit of metastable β titanium TNZ to around 3800–4000 μg/g, in order to obtain a favourable combination of strength and ductility.

Fig. 3 shows the results of tensile testing of MIM metastable β titanium TNZ(Y) with either aligned GB-TiC or dispersed intragranular TiC precipitates, which are produced by a novel TiC redistribution method (CSRA sintering pathway) which the authors outlined in a previous paper. This involves a dissolution and re-precipitation heat treatment, where the grain boundary TiC (GB-TiC) precipitated at high temperature and high diffusion rate and is transformed into intragranular TiC precipitated at low temperature and low diffusion rate in large quantities, thereby adjusting the spatial distribution of TiC particles from alignment along grain boundaries to dispersion within grains. The authors state that, by regulating the sintering temperature in the β phase-field mass, diffusion rates can be increased or decreased. In this way, it is possible to change the residual porosity and prior β grain size in sintered β titanium TNZY alloys.

Fig. 4 shows the tensile properties of as-sintered β TNZY alloys which were heat treated at 800°C for 1 hour just below α/β transus for different holding times in order to coarsen secondary α precipitates. This precipitate coarsening treatment was found to result in a significant improvement in elongation.

The authors also examined some defect-related factors that may affect the fatigue performance of sintered metastable β titanium alloys processed by MIM with surface quality being one of the most critical factors. Tests showed that shot peening enhanced the endurance limit (i.e. fatigue strength at 10^7 cycles) of MIM β TNZ alloys, and the results are shown in Fig. 5. It is clear that the fatigue life of samples without shot peening was less than one percent of that of the shot-peened ones. The authors noted that MIM metastable β TNZ provides superior fatigue performance, even ca. 150 MPa higher than MIM Ti6Al4V prepared by the prealloyed method. There is however, so far, no other data available in the literature to compare the fatigue properties of β titanium alloys processed by other PM routes.

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Calling all product designers: Discover what Metal Injection Moulding could do for you through these award-winning parts

Metal Injection Moulding is one of the most capable manufacturing processes for small precision components, yet it is also one of the least known. MIM parts are everywhere, from smartphones to watches, cars to aircraft – but these examples are rarely noticed by those outside of the industry. Here, we present the fourteen award-winning MIM parts from the Metal Powder Industries Federation's 2022 Powder Metallurgy Design Excellence Awards. These examples offer an insight into the technology, as well as the opportunity for product designers and engineers to consider how they might use MIM in their own projects.

A significant number of parts produced by Metal Injection Moulding were amongst the winners in the 2022 Powder Metallurgy Design Excellence Awards competition, sponsored by the Metal Powder Industries Federation (MPIF). These components showcase outstanding examples of MIM's unique ability to challenge competing technologies. From lightweighting to complex geometries, MIM provides component designers with the ability to utilise advanced engineering methods that add up to part-to-part uniformity for improved product quality; shape and material flexibility; application versatility, and more.

From a product designer or production engineer's perspective, these award-winning parts offer an opportunity to study how various industries, from consumer goods to aerospace, automotive and medical are leveraging the advantages of MIM. Whatever industry you are in, take the opportunity to see how others are using MIM, and consider how the technology could benefit your business.

Many of MIM's basic design considerations can be seen throughout, including the choice of injection points, ejector pin positions, the removal of unnecessary material, etc. The various achievable surface finishes are also visible. We hope that these parts inspire you to consider MIM as a production process.

Grand Prize

AUTOMOTIVE CATEGORY:

Kyerim Metal Co., Ltd for Hyundai
A Grand Prize in the Automotive Chassis category for metal injection moulded components was awarded to Korea's Kyerim Metal

Fig. 1 A 316L stainless steel rotary wheel used in an automotive interior (Courtesy MPIF)

Fig. 2 A fire control housing for the trigger mechanism in a consumer pistol (Courtesy MPIF)

Fig. 3 A rotor flow metre used in an agricultural sprayer (Courtesy MPIF)

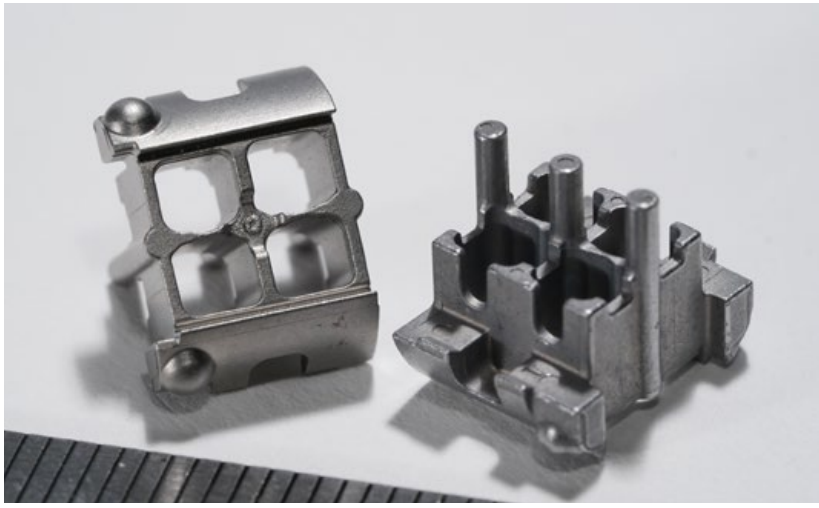


Fig. 4 Components for a quick-change core retaining anti-drill part used in a security door lock assembly (Courtesy MPIF)

Co., Ltd, and customer Hyundai Motor Company, Korea, for a 316L stainless steel rotary wheel used for selecting various internal functions in Hyundai-Kia Automotive Group automobiles (Fig. 1). The MIM part replaced an electroplated plastic rotary wheel and exhibits more than four times the durability of the plastic part.

MIM automotive interior parts, along with parts produced by Ceramic Injection Moulding, are seeing increased use in automotive interiors as manufacturers look to increase the perceived levels of quality in premium vehicles, in particular from an aesthetic and haptic perspective.

AEROSPACE/MILITARY/FIREARMS CATEGORY:

ARC Group Worldwide for Palmetto State Armory

In the Aerospace/Military/Firearms category for MIM components, a Grand Prize was awarded to ARC Group Worldwide, Denver, Colorado, USA, and their customer Palmetto State Armory, Columbia, South Carolina, for a fire control housing that holds the trigger mechanism in a consumer pistol firearm (Fig. 2). The fire control housing mounts into the frame of a pistol and supports various fire control mechanism components. The part facilitates the assembly of the firearm and supports the sear and blocker safety components. MIM is used extensively for the production of sporting and military firearms worldwide, bringing the benefits of the cost-effective, high-volume production of precision components in a wide range of performance materials.

LAWN & GARDEN/OFF-HIGHWAY CATEGORY:

Indo-MIM Pvt Ltd

In the Lawn & Garden/Off-Highway category for MIM components, a Grand Prize was awarded to Indo-MIM Pvt Ltd., Hoskote, India, and San Antonio, Texas, USA, for a rotor flow metre used in an agricultural

sprayer made from 17-4 PH stainless steel (Fig. 3). The rotor is used to measure the flow rate of pesticide or fertiliser that passes through an extended boom on either side of a carrier while spraying a field. The rotors were previously machined. MIM processing was more cost-effective than competing processes.

HAND TOOLS/RECREATION CATEGORY:

Indo-MIM Pvt Ltd
Indo-MIM also received a Grand Prize in the Hand Tools/Recreation category for MIM components for a quick-change core retaining anti-drill part used in a security door lock assembly (Fig. 4). The complex part requires high strength and good wear resistance and is made from M2 tool steel. The cube-like structure has four square through-holes and, across its centre, three cylindrical projections, one at each edge and one in the centre. The lock industry is a major market for MIM, thanks to its ability to deliver high volumes of net shape components, eliminating the need to post-process components that are often made of hard to machine materials.

MEDICAL/DENTAL CATEGORY:

Indo-MIM Pvt Ltd
In the Medical/Dental Category for MIM components, a Grand Prize was also awarded to Indo-MIM for a stainless steel curved jaw, part of an advanced bipolar device designed for use in open or laparoscopic tissue sealing surgical procedures (Fig. 5).
For decades, the MIM industry has been relied upon to produce many millions of high-precision single-use surgical instruments in stainless steel. The use of single-use surgical instruments is now commonplace, reducing the risk of infection, and MIM's ability to cost-effectively deliver extremely small, complex components and assemblies revolutionised the surgical device industry.

Fig. 5 A stainless steel curved jaw, part of an advanced bipolar device designed for use in open or laparoscopic tissue sealing surgical procedures (Courtesy MPIF)

"The use of single-use surgical instruments is now commonplace, reducing the risk of infection, and MIM's ability to cost-effectively deliver extremely small, complex components and assemblies revolutionised the surgical device industry."

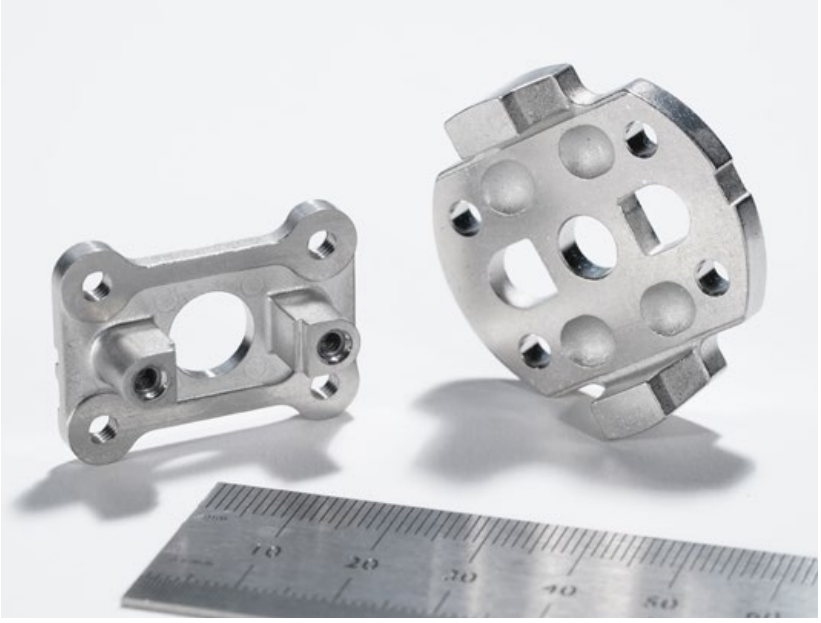


Fig. 6 A stator assembly – plate and frame – used in small aerospace servo valves (Courtesy MPIF)

Fig. 7 Vane levers used as gas flow controllers in the turbochargers of internal combustion engines (Courtesy MPIF)

"MIM's ability to manufacture high volumes of hard to machine components to net shape has seen it achieve considerable success in the automotive turbocharger market."

ELECTRONIC/ELECTRICAL COMPONENTS CATEGORY:

ARC Group Worldwide
In the Electronic/Electrical Components Category for MIM components, a Grand Prize was awarded to ARC Group Worldwide for a stator assembly (plate and frame) used in small aerospace servo valves (Fig. 6). Both parts are produced using two-cavity, three-plate injection moulds. The stator assembly is part of a flux-carrying device that delivers magnet and coil flux to an armature. The assembly is used in servo valves for flight control actuation. MIM technology offered an opportunity to produce this assembly at a significantly reduced cost. MIM components have been used in the aerospace industry for decades, with applications areas ranging from seat-buckle components to superalloy stator vanes.

Awards of Distinction

AUTOMOTIVE—ENGINE CATEGORY:

Indo-MIM Pvt Ltd
In the Automotive—Engine Category for MIM components, an Award of Distinction was given to Indo-MIM Pvt Ltd., for a vane lever used as a gas flow controller in the turbocharger of an internal combustion engine (Fig. 7). The MIM part is made using HK30 austenitic stainless steel that has good oxidation resistance and strength at operating temperatures of 800–850°C. The part was previously made by machining wrought bar stock. MIM's ability to manufacture high volumes of hard to machine components to net shape has seen it achieve considerable success in the automotive turbocharger market.

AUTOMOTIVE—CHASSIS CATEGORY

Indo-MIM Pvt Ltd
In the Automotive—Chassis Category for MIM components, an Award of Distinction was given to Indo-MIM Pvt Ltd., for an upper cap, lower cap,

split centre, and split centre bleed for a high-end automotive suspension system sub-assembly (Fig. 8). The parts are made from MIM-4605 and heat treated. MIM technology offers an advantage over other production processes in being able to deliver significantly increased shape complexity for suspension system components whilst remaining cost effective for high production volumes.

Fig. 8 An upper cap, lower cap, split centre, and split centre bleed for a high-end automotive suspension system (Courtesy MPIF)

AEROSPACE/MILITARY/FIREARMS CATEGORY:

OptiMIM, a Form Technologies Company
In the Aerospace/Military/Firearms Category for MIM components, an Award of Distinction was given to OptiMIM, a Form Technologies Company, Charlotte, North Carolina, USA, and their customer Savage Arms Inc., Westfield, Massachusetts, USA, for a MIM-4605 bolt end-cap for an SPR Impulse rifle (Fig. 9). The bolt end-cap has a large, open-structure shape with four side holes. It has comparatively thin walls in relation to its size

Fig. 9 Bolt end-caps for an SPR Impulse rifle (Courtesy MPIF)

Advanced Powder Products Inc.
In the Aerospace/Military/Firearms Category for MIM components, an Award of Distinction was given to Advanced Powder Products Inc., Philipsburg, Pennsylvania, USA, for a one-piece slide release for a firearm (Fig. 10). The part is made from an air quenched and tempered S7 tool steel. The part was originally designed for stamping, but the complex geometry was too much of a challenge for this technology.

Fig. 10 A one-piece slide release for a firearm (Courtesy MPIF)

HAND TOOLS/RECREATION CATEGORY:

ARC Group Worldwide
In the Hand Tools/Recreation Category for MIM components, an Award of Distinction was given to ARC Group Worldwide for a lock-arm button used in a pocket knife (Fig. 11). When depressed, the button

Fig. 11 A lock-arm button used in a pocketknife (Courtesy MPIF)

Fig. 12 Components for a control cone used as a fluid controller in a fuel pump (Courtesy MPIF)

fires the blade open or allows the operator to close the cutting tool safely. The part is made from MIM-420 stainless steel and hot isostatically pressed (HIPed) after sintering. The HIP process is typically used to remove final porosity, resulting in an improved as-polished surface finish. MIM is widely used for the production of handheld multi-tools, nail clippers and other household items. Note that with MIM, textures can be produced in the tooling rather than added post-production.

INDUSTRIAL MOTORS/CONTROLS & HYDRAULICS CATEGORY:

Indo-MIM Pvt. Ltd

An Award of Distinction was given to Indo-MIM Pvt. Ltd. in the Industrial Motors/Controls & Hydraulics Category for MIM components produced for a control cone used as a fluid controller in a fuel pump. This is a highly complex part with a cylindrical stepped outer diameter that tapers like a dovetail towards one end. The part was previously machined, and producing the angular hole required difficult high-volume machining. MIM proved to be the most suitable technology for high-volume production.

PTI (Polymer Technologies Inc. and Schindler Elevator Corp

An Award of Distinction in the Industrial Motors/Controls & Hydraulics Category for MIM components was given to PTI (Polymer Technologies Inc.) and its customer Elevator Products Corporation (a division of Schindler Elevator Corp.), for an elevator button assembly that is impervious to solvents and disinfectants (Fig. 13).

These parts solved a problem encountered during the COVID-19 pandemic – elevator button assemblies machined from stainless steel and over-moulded with polycarbonate threaded inserts were being degraded by the various solvents and disinfectants used to sterilise highly touched areas in elevators.

Fig. 13 An elevator button assembly that is impervious to solvents and disinfectants. The inset image shows the larger part as-sintered part prior to machining of the thread (Courtesy MPIF)

MEDICAL/DENTAL CATEGORY:

ARC Group Worldwide
In the Medical/Dental Category for MIM components, an Award of Distinction was given to ARC Group Worldwide for a MIM 14-4PH impaction handle lever, a single-use-instrument used in knee-replacement surgery (Fig. 14). Tight profiles are maintained in relation to the distal end of the instrument to ensure proper engagement with mating parts. This impaction handle lever represents one of the first single-use instruments converted from plastic to Metal Injection Moulding.

Fig. 14 Impaction handle lever used in a single-use-instrument for knee-replacement surgery (Courtesy MPIF)

Further information

For further information on designing for Metal Injection Moulding, visit the *PIM International* website, where all past issues of this magazine are available to download free of charge, as well as a guide to optimising designs for MIM production, featured within our 'About PIM' pages.

The Metal Powder Industries Federation (MPIF) website, and that of its Metal Injection Molding Association (MIMA), also include significant resources on MIM, including past award winners from this competition and a directory of member part producers.

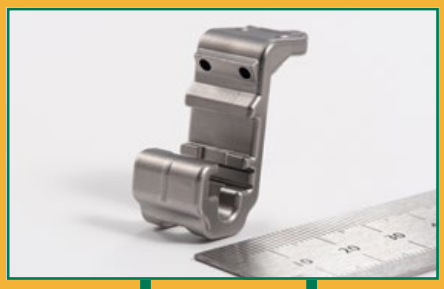
www.pim-international.com
www.mpif.org
www.mimaweb.org

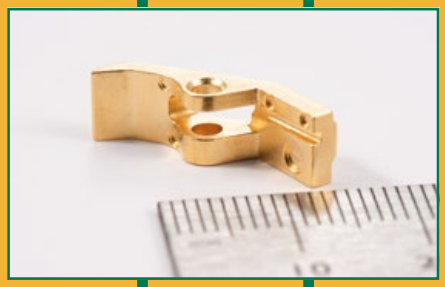
ABSTRACT SUBMISSION DEADLINE: SEPTEMBER 30, 2022

MIM 2023

International Conference on Injection Molding of Metals, Ceramics and Carbides

February 27–March 1, 2023 • Hilton Orange County/Costa Mesa, CA





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Binder Jetting of a dual-phase steel: Process insight and optimisation using the Master Sintering Curve

Binder Jetting (BJT) is never far from the headlines in the worlds of Powder Metallurgy and Additive Manufacturing, but, whilst there has been a lot of emphasis on Binder Jetting's build process, the crucial sintering stage has received less attention. Can we really go along with the assumption that it's 'just like sintering for Metal Injection Moulding'? Here, Markus Schneider and colleagues from GKN Sinter Metals Engineering GmbH, GKN Additive and Hoeganaes Corporation bring together their deep expertise in sintering to reveal just how differently metal BJT parts perform, and what implications there are for part design and future process optimisation.

The Master Sintering Curve (MSC) is a useful tool to compare different sintering profiles regarding their effect on material shrinkage, especially for fine powders. This is reached by the stepwise contraction of sintering temperature and sintering time to a common sintering parameter, and its sigmoidal correlation to the densification parameter as a measure of the sintering response. The underlying sintering kinetics are investigated in terms of the process's activation energy. Similar to Metal Injection Moulding, metal Binder Jetting is a two-stage Additive Manufacturing process, whose sintering behaviour is characterised by the significant material shrinkage that takes place before the components' final geometry and density is reached. Fig. 1 shows parts entering an industrial-scale continuous sintering furnace.

In this study, a newly developed dual-phase steel, which can be tailored for a variety of strength/ductility combinations, is characterised by dilatometric sintering trials and a subsequently generated Master Sintering Curve. The findings presented suggest that, due to 'textures' introduced by the layer-by-layer BJT process, the resulting material shrinkage exhibits an anisotropic behaviour, which must be carefully considered.

Compared with laser-based Additive Manufacturing processes – in particular Laser Beam Powder Bed Fusion (PBF-LB) – metal Binder Jetting is more energy-efficient when it comes to industrial production volumes. However, whilst it has similarities to Metal Injection Moulding, there are still a few hurdles which hinder its wider application:

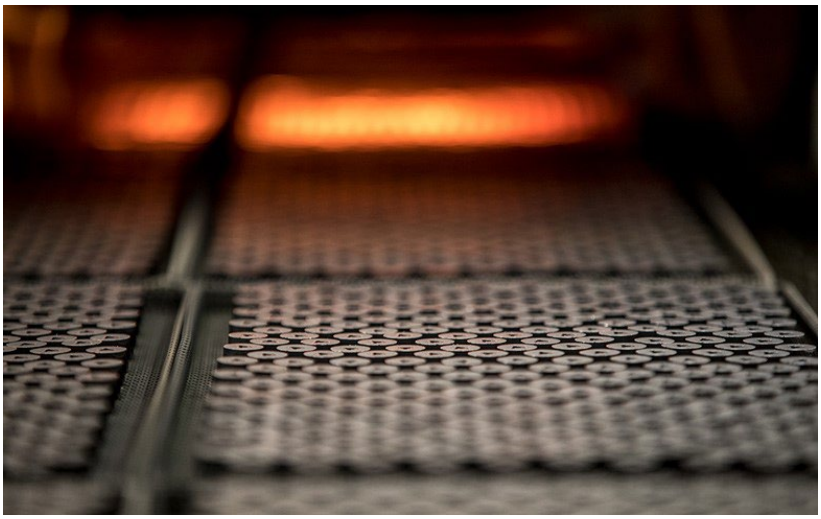


Fig. 1 The importance of process optimisation specifically relating to industrial-scale sintering for metal Binder Jetting should not be underestimated (Courtesy GKN PM)

Fig. 2 Binder Jetting development has been taking place since 2019 at GKN Powder Metallurgy's Bad Langensalza plant using HP Metal Jet machines (Courtesy HP/GKN PM)

> *"Inhomogeneous and anisotropic volumetric shrinkage exists... due to an initial powder, binder and layer distribution that is not fully isotropic, as well as temperature distribution variations within the sintering furnace..."*

Component size
The maximum size (dead weight) of the component is limited to prevent sinking/sagging due to insufficient support from the surrounding powder bed.

Surface finish
Final surface roughness Ra and Rz depend on the layer thickness x and the (typically manual) depowdering strategy and process as a whole.

Shrinkage characteristics
Inhomogeneous and anisotropic volumetric shrinkage exists ε_{3D} due to an initial powder, binder and layer distribution that is not fully isotropic, as well as temperature distribution variations within the sintering furnace, within the component and between components on the sintering tray.

Creep effects
Superimposed creep effects can lead to further deformations.

Material availability
Limited materials are available which are of interest to the automotive and machinery industries.

Overview of sintering profile development

Sintering and creep are two related phenomena occurring in similar temperature ranges T (homologue Tammann temperature $T_D \approx 0.4T_m$ for pure metals and $T_D \approx 0.6T_m$ for alloys) and with similar activation energies ($Q_s \approx Q_c$). This observation is based on one of Professor Gustav Tammann's favourite experiments: the stirrer experiment in which a stirrer with a minimum of torque whisked through a heated metal powder column. The temperature T when the stirrer stopped due to an increased friction (the start of sintering) was recorded and normalised to the metal powders melting temperature T_m. In general, sintering is related more to the volumetric change of a component under the influence of the applied hydrostatic stress σ_H (resistance against sintering: bulk viscosity K), whereas creep affects the geometric shape of a component under the influence of the deviatoric stress ε'_{ij} (resistance against creep: shear viscosity G).

However, in continuum mechanical sintering modelling, both effects are incorporated into the commonly used material law $\varepsilon'_{ij}=\sigma'_{ij}/2G+\delta_{ij}(\sigma_H-\sigma_s)/3K$. Thus, the strain rate ε'_{ij} (total deformation) is the weighted sum of both terms. The weighting depends on the porosity f present and the applied stress σ [1, 2].

Prior to the application of the Master Sintering Curve, it is worth reconsidering the other existing sintering parameters, which combine the sintering time t and the sintering temperature T into a single parameter to characterise the intensity of the sintering and the corresponding resultant material quality. This approach is not new; there has always been an effort to predict the sintered density ρ from the sintering profile T(t), because most material properties exhibit quite a good correlation.

Professor Paul Beiss adopted the Larson-Miller parameter P_{LM} from creep mechanics (for example, to accelerate the time-consuming creep experiments by using higher temperature levels) to differentiate High Temperature Sintering (HTS) treatments from conventional sintering runs. Due to the previously mentioned similarities between sintering and creep, this idea is straightforward. A more detailed view on the derivation of the Larson-Miller parameter P_{LM} notes its relation to the Monkman-Grant creep law and the Arrhenius activation equation.

The Larson-Miller parameter P_{LM} is defined as:

$$P_{LM}=T(\log(t)+20)$$

By introducing the reference time of t_0=1 h into this equation, the inconsistency of the unit can be avoided, and the resulting unit of the Larson-Miller parameter P_{LM} is Kelvin:

$$P_{LM}=T(\log(t/t_0)+20)$$

The same, or a very similar parameter, can also be found in the heat-treating community. The Hollomon-Jaffe parameter P_{HJ} is commonly used to define tempering time t and tempering temperature T and for the derivation of Master Tempering Diagrams (correlation between the Hollomon-Jaffe parameter P_{HJ} and the hardness H), as:

$$P_{HJ}=P_{LM}/1000$$

However, all definitions can only deal with rectangular (isothermal) sintering profiles T(t). This disadvantage is solved by the adoption of sintering work $\theta(t, T)$ in the MSC, which is more flexible and can incorporate the contribution of the heating and cooling phases. Another commonly used sintering parameter is the penetration depth x of an atom into the crystallographic host lattice as a metric for the intensity of the diffusion:

$$x=2(Dt)^{0.5}$$

The penetration depth x is often used to characterise the response of thermochemical surface treatments like case hardening (interstitial carbon diffusion) or nitriding (interstitial nitrogen diffusion). The equation tells us that a fourfold time is needed to double the case hardening depth x=CHD or nitriding hardness depth x=NHD. The diffusion coefficient D is temperature-dependent and is linked to the Arrhenius activation equation as:

$$D_i=D_{0,\,i}\exp(-Q_i/RT)$$

This equation is the basis for the Arrhenius plot and the kinetic field approach. The penetration depth x is a function of the transient concentration distribution C(x, t) described over the Gaussian error function (2nd Fick's law of diffusion) as:

$$C(x, t)=C_\infty-(C_\infty-C_0)\mathrm{erf}(x/(2(Dt)^{0.5})$$

This equation describes the concentration distribution C(x, t) from the surface concentration C_∞ to initial concentration C_0 as a function of time t. For $x=2(Dt)^{0.5}$, the function within the bracket becomes unity and the Gaussian error function becomes erf(1)=0.8427. This means that, at the coordinate of x, there is a concentration gain of approx. 16% (1-0.8427=15.73%). The exact value is irrelevant. The penetration depth x has the same disadvantage as the Larson-Miller parameter P_{LM} (dealing with rectangular (isothermal) sintering profiles T(t) only).

The main problem in these sintering parameters is their link to the microscopic evolution of the sintering response. The use of coarse powders and/or a low homologue Tammann temperature T_D will suppress volumetric shrinkage ε_{3D} because the system will remain in the initial sintering stage I. Consequently, only indirect metrics for the sintering response and progress – for example, mechanical, electrical or thermal properties – can be used for their correlation with any of the sintering parameters, with all their drawbacks (the mechanical properties are more affected by the cooling rate $\Delta T/\Delta t$ after sintering).

Sintering neck formation and the resulting phase transformations can be monitored in laboratory sintering experiments (sphere/sphere, sphere/plate, cylinder/plate configurations, etc), but is not possible using real powders. This limits this methodology to material systems which undergo the intermediate sintering stage II and the final sintering stage III, because the volumetric shrinkage ε_{3D} is a direct metric for the sintering response.

FSLA dual-phase steel

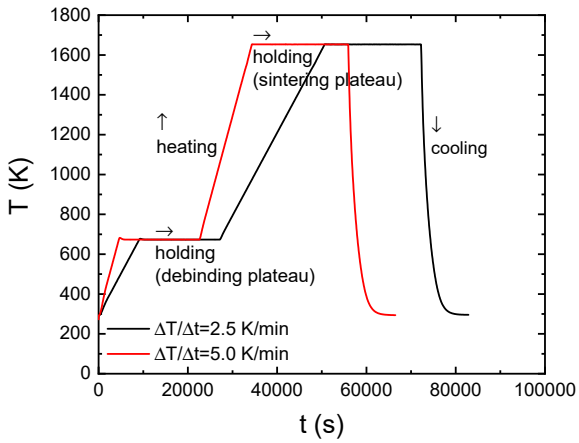
A newly developed dual-phase Free Sintering Low Alloy (FSLA) steel was used and further characterised by dilatometric sintering trials on binder jetted materials. FSLA is a gas atomised Fe + 0.20% Mn + 1.60% Cr + 1.45% Mo + 1.54% Si + 0.15% C alloy with a high degree of sinterability, which offers a wide range of strength/ductility combinations. The composition was modified in such a way that sintering takes place in the body-centred cubic (bcc) crystallographic lattice structure rather than in the face-centred cubic (fcc) crystallographic lattice structure. The more open bcc crystallographic lattice structure exhibits higher self-diffusion coefficients.

Its dual-phase (martensite-ferrite) microstructure with precipitated carbides results in a characteristic ultimate tensile strength (UTS) of σ_u=600 MPa, very similar to the DP600 dual-phase material class. The martensitic phase is responsible for strength, whereas the low carbon ferrite offers ductility. Depending on the heat treatment schedule, the yield strength can be varied between $\sigma_{0.2}$=379 MPa and $\sigma_{0.2}$=481 MPa and the ultimate tensile strength can be varied between σ_u=650 MPa and σ_u=959 MPa.

The gas atomised FSLA material has a typical particle size of $d_{10}\approx$6 µm, $d_{50}\approx$15 µm and $d_{90}\approx$27 µm [3]. Cylindrical green specimens were built in X- (binder jet nozzle movement direction), Y- (recoater movement direction) and Z-direction (gravity direction), with a height of h≈7 mm and a diameter of d≈5 mm, using a layer thickness of x=70 µm on an HP Metal Jet BJT machine (Fig. 2). The resulting green densities ρ_g can be found in Table 2.

Dilatometry

Dilatometric sintering runs are small-scale sintering experiments and deliver the raw data for the Master Sintering Curve. Thermodilatometric Analysis (TDA) is



Binder Jetting FSLA (HP),
dilatometry experiments at Linseis,
material: FSLA (HC),
dilatometer: Linseis L75 PT (horizontal single pushrod),
specimens: cylinders with d≈5 mm and h≈7 mm,
ρ_g=4.47/4.32/4.33 g/cm³, ρ_0=7.86 g/cm³,
printed in X-direction, Y-direction and Z-direction,
heating rate: ΔT/Δt (see above),
debinding plateau: T=673.15 K, t=18000 s,
sintering plateau: T=1653.15 K, t=21600 s,
cooling rate: ΔT/Δt (free cooling),
atmosphere: 100 % H_2,
corrected thermal expansion: α=CTE=10*10^{-6} K^{-1}

Fig. 3 Sintering profiles applied on FSLA with two different heating rates ΔT/Δt to investigate 'fast firing' sensitivity

a special case of Thermomechanical Analysis (TMA) with negligible loads (TDA is often called 'zero force TMA'); both methods belong to the Thermal Analysis (TA) family [4,5].

There are two kinds of dilatometer available on the market. Pushrod dilatometers record only the linear axial shrinkage (ε_{axial}). Their accuracy depends on the shape of the cylindrical specimen used (tilting of non-perfect cylinders during gripping with the pushrod). Friction is minimised in horizontal pushrod dilatometers by a line contact between the lateral specimen surface and the surrounding gripping unit. An axial contact force (F_{axial}) maintains the contact to the pushrod [4,5].

Optical dilatometers record the linear axial shrinkage (ε_{axial}) and the linear lateral shrinkage ($\varepsilon_{lateral}$) in a simultaneous manner. The beauty of this Thermal Optical Measurement (TOM) is that the sintering process can be observed in-situ [6]. The accuracy is not affected by tilting, but the optical signals must be filtered several times due to flickering of the hot protective gas inside the optical dilatometer and a subsequent video image analysis is needed. Since there is no pushrod, there is no possible falsification of the linear axial shrinkage (ε_{axial}) from the applied axial contact force (F_{axial}). However, the investment costs for an optical dilatometer are far higher than the costs for a pushrod dilatometer.

	ΔT/Δt (K/min)	t (s)	T (K)
Heating up from room temperature to debinding temperature	2.5 and 5		
Debinding		18,000	673.15
Heating up from debinding temperature to sintering temperature	2.5 and 5		
Sintering		21,600	1,653.15
Cooling down from sintering temperature to room temperature	Not controlled, over convection		

Table 1 Chosen sintering profiles, debinding and sintering plateaux applied on FSLA with two different heating rates ΔT/Δt

The corresponding (final) sintered density (ρ_s) is calculated in both cases (the negative sign is dropped in this formulation) as $\rho_s=\rho_g/(1-(\Delta L/L_0))^3$. In this equation, ρ_g denotes the green density, whereas the linear axial shrinkage is calculated as $\varepsilon_{axial}=\Delta L/L_0$. For a better comparison of materials having different green densities ρ_g, theoretical densities ρ_0 and (final) sintered densities ρ_s a further manipulation is needed. The dimensionless densification parameter ψ (defined between 0 and 1) is defined as $\psi=(\rho_s-\rho_g)/(\rho_0-\rho_g)$. The numerator ($\rho_s-\rho_g$) is a metric for the achieved densification and the denominator ($\rho_0-\rho_g$) defines the possible densification. However, in the case of pushrod dilatometers, isotropic shrinkage ($\varepsilon_{axial}=\varepsilon_{lateral}$) must be assumed. A problem will arise if the volumetric shrinkage ($\varepsilon_{3D}=\Delta V/V_0$) is anisotropic since information regarding the linear lateral shrinkage ($\varepsilon_{lateral}=\Delta D/D_0$) cannot be derived from conventional pushrod dilatometers.

Laboratory dilatometric sintering runs differ from industrial sintering runs due to the low thermal inertia of the cylindrical specimen used and the high heat transfer. Moreover, the heating rate (ΔT/Δt) can be defined and controlled in a narrow range. Two thermocouples are used for the control, whereas one thermocouple is located as close as possible beside the cylindrical specimen. The main benefit of this TA is that the linear

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material: FSLA (HC),
dilatometer: Linseis L75 PT (horizontal single pushrod),
specimens: cylinders with d≈5 mm and h≈7 mm,
ρ_g=4.47/4.32/4.33 g/cm³, ρ_0=7.86 g/cm³,
printed in X-direction, Y-direction and Z-direction,
heating rate: ΔT/Δt (see above),
debinding plateau: T=673.15 K, t=18000 s,
sintering plateau: T=1653.15 K, t=21600 s,
sintering plateau: T=1653.15 K, t=21600 s,
cooling rate: ΔT/Δt (free cooling),
atmosphere: 100 % H_2,
corrected thermal expansion: α=CTE=10*10^{-6} K^{-1}

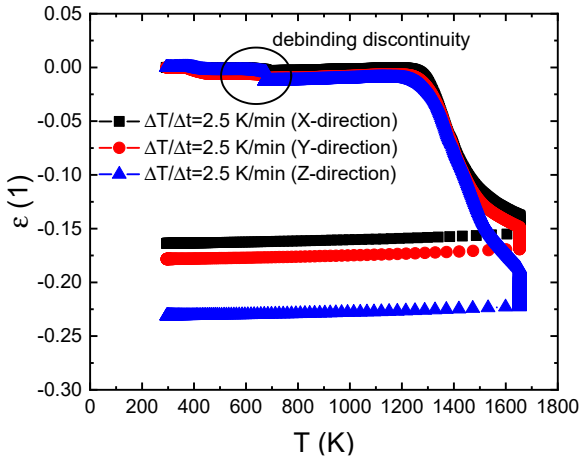

Fig. 4 Dilatometric sintering results (linear axial shrinkage ε_{axial}) of FSLA derived with a heating rate of ΔT/Δt=2.5 K/min

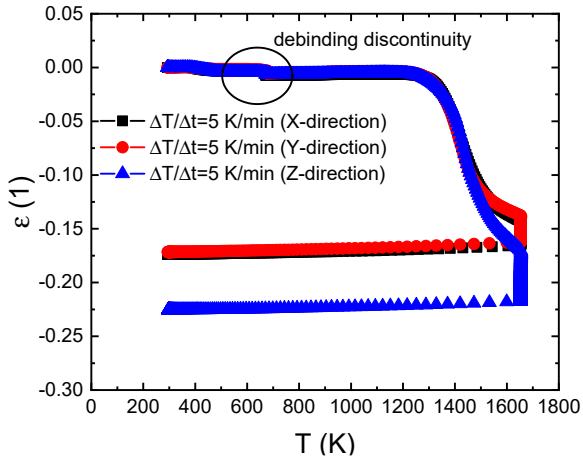

Fig. 5 Dilatometric sintering results (linear axial shrinkage ε_{axial}) of FSLA derived with a heating rate of ΔT/Δt=5 K/min

axial shrinkage (ε_{axial}) is recorded in a continuous manner. Therefore, the evolution of the linear axial shrinkage (ε_{axial}) as a function T(t) of the chosen sintering profile can be followed in detail. Nevertheless, the goal is the transferability (adjusting the industrial sintering parameters based on the results from the dilatometric sintering runs).

For this study, the linear axial shrinkage (ε_{axial}) of FSLA was measured with a pushrod dilatometer. The displacement (ΔL) is measured over the induction current via a linear variable differential transformer (LVDT). Since the dilatometry signal is superimposed on the thermal expansion of the pushrod and the cylindrical specimen, two corrections are needed. The thermal expansion of the pushrod is compensated by a 'dummy' dilatometric sintering run without a cylindrical specimen, while the thermal expansion of the cylindrical specimen is compensated by a correction term (CTE=10*10^{-6} K^{-1}). The chosen coefficient of thermal expansion of CTE=10*10^{-6} K^{-1} is very close to the Grüneisen rule estimation of CTE≈0.02/T_m [7]. That rule assumes a constant axial linear thermal expansion of $\varepsilon_{axial,\ thermal}$=2% in the melting temperature range T_m. FSLA exhibits a melting temperature of T_m≈1666.15 K. The current dilatometric sintering runs were conducted at Linseis in Selb with a Linseis L 75 PT dilatometer (horizontal single pushrod). An axial contact force of F_{axial}=250 mN was applied during the measurement to maintain the contact between the sample and the pushrod.

The effect from that axial contact force (F_{axial}) is negligible. For very accurate measurements, several measurements with different axial contact forces (F_{axial}) can be applied. Afterwards, the data points can be extrapolated to an axial contact force of F_{axial}=0 N. Pure hydrogen (100% H_2 with a flow of ΔV/Δt=10 l/h) was used as the sintering atmosphere. Fig. 3 and Table 1 define the applied sintering profiles.

Two different heating rates (ΔT/Δt) were chosen to identify potential dependencies. It is known within the Field-Assisted Sintering Techniques (FAST) that, at very high heating rates (ΔT/Δt) the densification can be enhanced by a suppressed grain coarsening. This effect is called 'fast firing' and depends on the corresponding activation energies for sintering Q_s and grain coarsening Q_g [8, 9]. However, the relevant heating rates (ΔT/Δt) for FAST are orders of magnitude higher than the applied ones.

The derived dilatometric sintering results of FSLA are shown in Figs. 4 and 5. The thermal expansion of the cylindrical specimen was successfully compensated. Both paths – the heating up and the cooling down phases – run horizontally in a parallel manner. Smaller discontinuities occur during the debinding at a temperature of T=673.15 K (ϑ=400°C). A potential reason for these discontinuities could be a small volumetric shrinkage of the cylindrical specimen arising from binder evaporation. During debinding, the cylindrical specimens became smaller. Due to this debinding discontinuity, the estimation of the coefficient of thermal expansion CTE is hardly possible in the heating up phase. The cooling down phase is more advantageous, due to the smooth progression of the debound cylindrical specimen. A significant densification and shrinkage started at a temperature of T≈1200 K. Obviously, this temperature T characterises the transition between the initial sintering stage I (particle rearrangement and sintering

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ρ_g=4.47/4.32/4.33 g/cm³, ρ_0=7.86 g/cm³,
printed in X-direction, Y-direction and Z-direction,
heating rate: ΔT/Δt (see above),
debinding plateau: T=673.15 K, t=18000 s,
sintering plateau: T=1653.15 K, t=21600 s,

cooling rate: ΔT/Δt (free cooling),
atmosphere: 100 % H_2,
corrected thermal expansion: α=CTE=10*10^{-6} K^{-1}

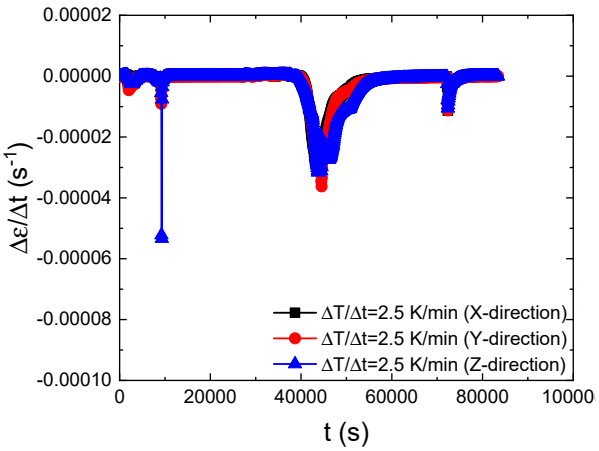

Fig. 6 Shrinkage rate Δε/Δt of the dilatometric sintering results (linear axial shrinkage ε_{axial}) of FSLA derived with a heating rate of ΔT/Δt=2.5 K/min

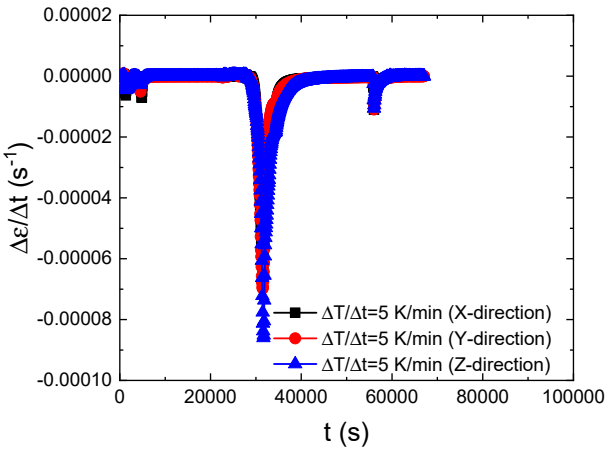

Fig. 7 Shrinkage rate Δε/Δt of the dilatometric sintering results (linear axial shrinkage ε_{axial}) of FSLA derived with a heating rate of ΔT/Δt=5 K/min

neck formation) and the intermediate sintering stage II (initial densification and initial grain coarsening) of the investigated FSLA material.

The isothermal sintering plateau has only a small influence on the whole densification and shrinkage process. Depending on the build direction in the BJT process, only an incremental linear axial shrinkage of ε_{axial}≈-3 % can be attributed to the isothermal sintering plateau with a dwell time of t=21600 s (t=6 h). Compared with the complete densification and shrinkage response, the application of such long dwell time t seems to be questionable. The basic build directions (X- and Y-directions) behave comparably, with their densification and shrinkage behaviours being very similar. The vertically built (Z-direction) cylindrical specimens shrink in a different way. They exhibit much higher linear axial shrinkage (ε_{axial}) values.

Consequently, it is very likely that the (final) sintered density (ρ_s) values and calculated densification parameters (ψ) are incorrect due to the wrong assumption of an isotropic shrinkage. Anisotropic shrinkage phenomena are not understood, on the whole. Often, it is found that the degree of anisotropy Ka=1-($\varepsilon_{axial}/\varepsilon_{lateral}$) decreases with increasing sintering progress [10]. Beside the conventional attempts at explanation (for example gravity and dead weight, inhomogeneous density distributions, residual stresses, cold deformations, different sintering mechanisms, crystallographic lattice orientations, trapped gases or different pore morphologies), most of the current attempts incorporate manufacturing-based textures (as observed in MIM, BJT, tape casting, extrusion and die pressing) [6, 10, 11, 12]. The derived results are summarised in Table 2 and Figs. 8 to 11.

A good approach to investigating the sintering kinetics in more detail is the derivation after time (t) of the dilatometric sintering results from Figs. 4 and 5. Events of higher or lower shrinkage rate (Δε/Δt) can be identified. An adjustment or control of the shrinkage rate (Δε/Δt) could be of interest if two different materials should be sintered together (co-sintering) without interface cracks or warpage, the material is very sensitive with regard to the applied

Build direction	ΔT/Δt (K/min)	ρ_g (g/cm³)	ε_{axial} (%), final	ρ_s (g/cm³), calculated	ψ (1), final
X	2.5	4.47	-16	7.65	0.94
Y	2.5	4.32	-18	7.79	0.98
Z	2.5	4.33	-23	9.53	1.47
X	5	4.47	-17	7.93	1.02
Y	5	4.32	-17	7.60	0.93
Z	5	4.33	-23	9.32	1.41

Table 2 Resulting final linear axial shrinkage ε_{axial}, final sintered density ρ_s and final densification parameter ψ of FSLA as function of build direction, heating rate ΔT/Δt and green density ρ_g

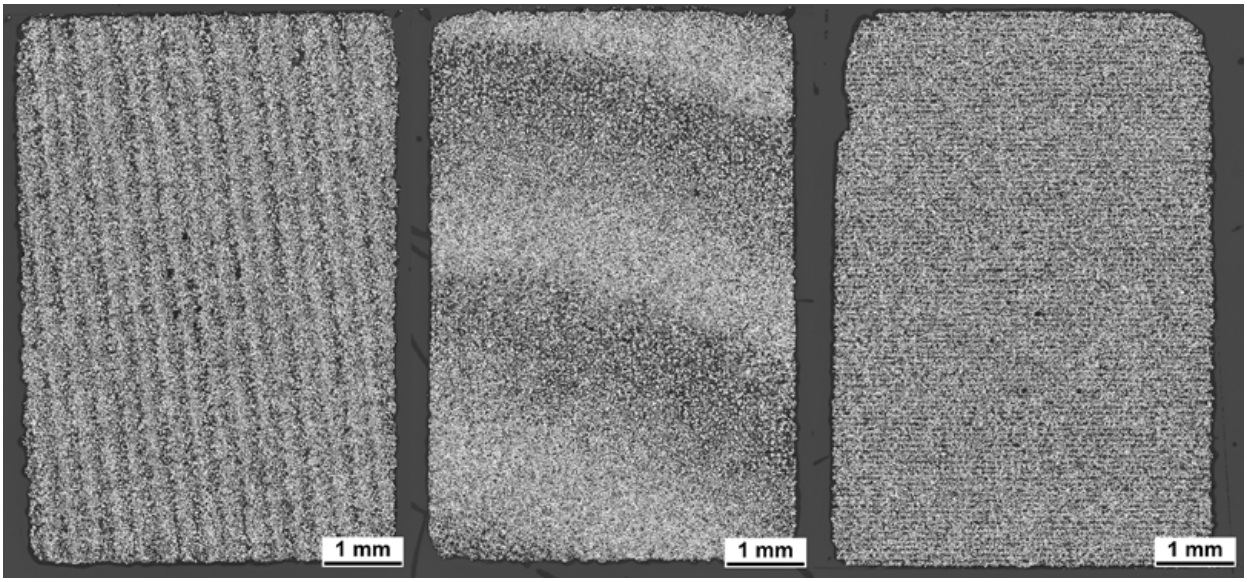

Fig. 8 Microstructures of the green components made of FSLA with its textures, X-direction (left), Y-direction (middle) and Z-direction (right)

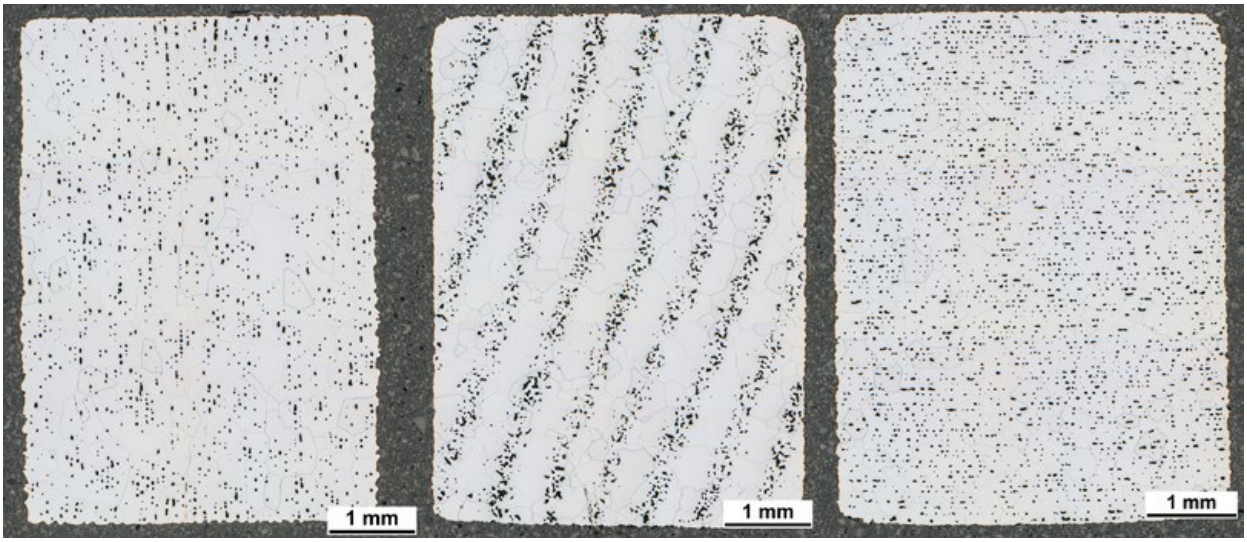

Fig. 9 Nital-etched microstructures of the sintered components made of FSLA ($\Delta T/\Delta t$=2.5 K/min) with its textures, X-direction (left), Y-direction (middle) and Z-direction (right)

shrinkage rate ($\Delta\varepsilon/\Delta t$) or if newer sintering concepts (e.g. the Palmour III shrinkage rate controlled sintering approach) should be applied. From Figs. 6 and 7 (and with the assistance of Fig. 3), the highest shrinkage rate ($\Delta\varepsilon/\Delta t$) is observed at T≈1400 K (long before the chosen maximum sintering temperature of T=1653.15 K). This location corresponds to the steepest slope of the dilatometric sintering results from Figs. 4 and 5. As a conclusion, a potential process optimisation could be the installation of a further sintering plateau in that region. The positive effect of optimised two-step or multiple-step sintering profiles T(t) is mentioned elsewhere. Moreover, further events – for example, the debinding plateau and the initial cooling down – can be identified.

The sintered microstructure and the evolution from the green state (see Fig. 8) to the sintered state (see Fig. 9) are very interesting. The manufacturing-induced textures (we could call them 'layered porosity') are clearly visible. The high-temperature sintering at a maximum sintering temperature of T=1653.15 K in the hydrogen pushrod dilatometer led to pronounced grain coarsening. If we assume an initial grain size G_{50} in the range of the particle size d_{50} (or smaller) of $G_{50}\approx d_{50}\approx 15$ µm, a massive grain coarsening up to grain sizes of G≈1 mm can be recognised. The images of the cylindrical specimens built in the X-direction and Z-direction indicate that most of the pores are located within the grain boundaries. That position can be assumed as an energy sink, which makes further densification and pore

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dilatometry experiments at Linseis,
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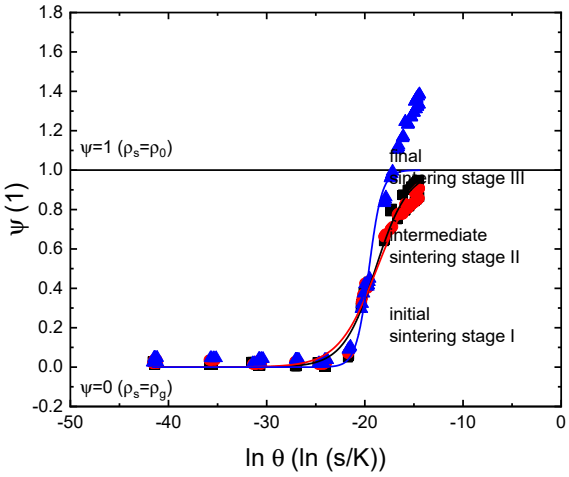
dilatometer: Linseis L75 PT (horizontal single pushrod),
specimens: cylinders with d≈5 mm and h≈7 mm,

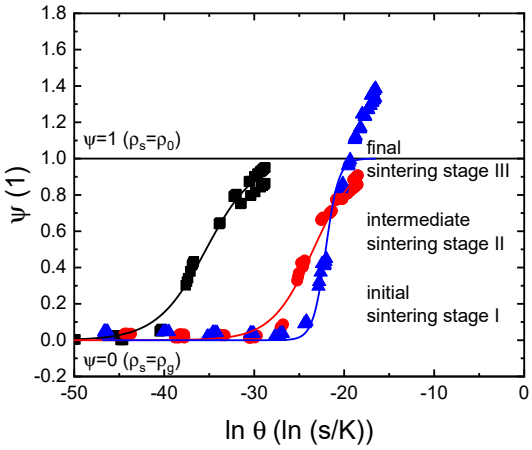
ρ_g=4.47/4.32/4.33 g/cm³, ρ_0=7.86 g/cm³,
printed in X-direction, Y-direction and Z-direction,
heating rate: ΔT/Δt (see above),
debinding plateau: T=673.15 K, t=18000 s,
sintering plateau: T=1653.15 K, t=21600 s,

cooling rate: ΔT/Δt (free cooling),
atmosphere: 100 % H_2,
corrected thermal expansion: α=CTE=10*10^{-6} K^{-1}



■ MSC, X-direction (ΔT/Δt=5 K/min and ΔT/Δt=2.5 K/min), Q_{MSC}=Q_s=235 kJ/mol, a=-18.9116 ln (s/K), b=1.6542
● MSC, Y-direction (ΔT/Δt=5 K/min and ΔT/Δt=2.5 K/min), Q_{MSC}=Q_s=235 kJ/mol, a=-18.7675 ln (s/K), b=1.9648
▲ MSC, Z-direction (ΔT/Δt=5 K/min and ΔT/Δt=2.5 K/min), Q_{MSC}=Q_s=235 kJ/mol, a=-19.5745 ln (s/K), b=0.6625

Fig. 10 MSC's of FSLA derived with a heating rate of ΔT/Δt=2.5 K/min and ΔT/Δt=5 K/min with a common apparent activation energy of Q_{MSC}=Q_s=235 kJ/mol



■ MSC, X-direction (ΔT/Δt=5 K/min and ΔT/Δt=2.5 K/min), Q_{MSC}=431 kJ/mol, a=-35.3514 ln (s/K), b=2.7261
● MSC, Y-direction (ΔT/Δt=5 K/min and ΔT/Δt=2.5 K/min), Q_{MSC}=290 kJ/mol, a=-23.4247 ln (s/K), b=2.3226
▲ MSC, Z-direction (ΔT/Δt=5 K/min and ΔT/Δt=2.5 K/min), Q_{MSC}=263 kJ/mol, a=-22.0505 ln (s/K), b=0.7162

Fig. 11 MSC's of FSLA derived with a heating rate of ΔT/Δt=2.5 K/min and ΔT/Δt=5 K/min with individually estimated apparent activation energy Q_{MSC} values

shrinkage without pressure-assisted and/or field-assisted sintering techniques such as Hot Isostatic Pressing (HIP), Powder Forging (PF) or FAST impossible. Only pores located on the grain boundaries have the chance to heal. Overemphasised grain coarsening will hinder the final densification [11, 13, 14].

Master Sintering Curve

A plot of the (final) relative sintered density (ρ_s/ρ_0), or of the densification parameter (ψ) over the sintering time (t), or the sintering temperature (T) delivers a sigmoidal-shaped curve (first asymptote: ρ_s=ρ_g, second asymptote: ρ_s=ρ_0), which can be converted into the MSC to incorporate the whole sintering profiles T(t). As shown in Figs. 10 and 11, the MSC is a plot of the densification parameter (ψ) over the logarithmic sintering work ln θ(t, T) with two free parameters a and b [12-21]:

$$\theta(t, T)=\int 1/T(t)\exp(-Q_{MSC}/RT(t))dt$$
$$\text{with } \psi=1/(1+\exp((-\ln \theta(t, T)-a)/b))$$

For the simplification of the data analysis, all data points below the homologue Tamman temperature of T_D≈666.46 K (chosen: T_D=673.15 K [ϑ=400°C due to the debinding plateau]) were not considered, since they do not contribute to the densification and shrinkage. All three sintering stages can be identified from the MSC:

Initial sintering stage I
Particle rearrangement and sintering neck formation accompanied by no shrinkage (powder particle centres remain in position)

Intermediate sintering stage II
Initial densification and initial grain coarsening accompanied by shrinkage (powder particle centres move towards each other)

Final sintering stage III
Final densification, pore separation and final grain coarsening (powder particle centres move towards each other)

The minimisation of the residuals delivers the apparent activation energy (Q_{MSC}) as described in [21]. However, as the initial setting, the apparent activation energy (Q_{MSC}) was estimated with the Engel-Brewer theory as Q_{MSC}=Q_s=RT_m(16+V)=235 kJ/mol (with V=1 for a bcc crystallographic lattice structure) as shown in Fig. 10 [12]. The derived (by the minimisation of the residuals) apparent activation energies (Q_{MSC}) differ significantly between the three build directions. This affects the sintering process θ(t, T), as shown in Fig. 11. The found apparent acivation energy Q_{MSC} values are given in Table 3. Therefore, the 'resistance against densification and shrinkage' depends on the build direction. It seems that the cylindrical specimens built in

Build direction	Q_{MSC} (kJ/mol):
X	431
Y	290
Z	263

Table 3 Apparent activation energy Q_{MSC} values as function of build direction

the Z-direction exhibit the lowest apparent activation energy with Q_{MSC}=263 kJ/mol (see Table 3).

The second asymptote of the sigmoidal-shaped MSC is touched, but not completely reached. Therefore, it can be concluded that the final sintering stage III is not fully reached, which corresponds to the microscopic observations (see Fig. 9) and the residual porosity (f) above.

The vertically built (Z-direction) cylindrical specimens overshoot the maximum dimensionless densification parameter of ψ=1. This is physically incorrect; a relic of the wrong assumption of isotropic shrinkage. The basic build directions (X-direction and Y-direction) must exhibit lower linear lateral shrinkage ($\varepsilon_{lateral}$) values to maintain the theoretical density of ρ_0=7.86 g/cm^3 and to compensate for the very high linear axial shrinkage values of ε_{axial}(Z-direction)=-23% (averaged between the two heating rates $\Delta T/\Delta t$). Unfortunately, that hypothesis cannot be verified with pushrod dilatometers. A subsequently performed calliper measurement of the lateral dimension (further differentiation between the basic build directions of the diameter d is not possible) of the final sintering state led to $\varepsilon_{lateral}$(Z-direction)=-13 % ($\Delta T/\Delta t$=2.5 K/min) and $\varepsilon_{lateral}$(Z-direction)=-14 % ($\Delta T/\Delta t$=5 K/min). As a result, the dimensionless densification parameter exhibits more realistic values with ψ<1.

The measurements of all other linear lateral shrinkage values $\varepsilon_{lateral}$(X-direction) and $\varepsilon_{lateral}$(Y-direction) are not meaningful because the diameter d is affected by shape deviations from the anisotropic shrinkage. From the individual apparent activation energies (Q_{MSC}) from Fig. 11, we can see that the sintering kinetics are also affected by the build direction. Even if the activation energy for self-diffusion Q_s of bulk materials depends only on the chemical system (diffusion partners), the crystallographic host lattice structure and the diffusion path, two other dependencies can be assumed for particulate materials: the effect of the particle size d_{50} and of the manufacturing-induced texture, or layered porosity.

Final conclusions

From the obtained results, we can draw several conclusions. Firstly, the intermediate sintering stage II starts and the initial sintering stage I ends at T≈1200 K. The highest shrinkage rate $\Delta\varepsilon/\Delta t$ is observed at T≈1400 K (far below the chosen maximum sintering temperature of T=1653.15 K). The final sintering stage III is not reached, due to the larger pores remaining inside the grains. Secondly, a debinding discontinuity appears at a temperature of T=673.15 K during the heating stage. It is not seen during cooling. Further, a coefficient of thermal expansion of CTE=10*10^{-6} K^{-1} leads to horizontal and parallel heating up and cooling down phases. The cooling down phase is much smoother and therefore better for the derivation of the coefficient of thermal expansion CTE.

This study found that there is no effect of the applied heating rates $\Delta T/\Delta t$ visible. Moreover, the basic build directions (X- and Y-direction) have no effect on the final linear axial shrinkage ε_{axial} (ε_{axial}(X-direction)=ε_{axial}(Y-direction)=-17% (averaged between the two heating rates $\Delta T/\Delta t$)), whereas the final linear axial shrinkage ε_{axial}(Z-direction) of the vertically built cylindrical specimens is much higher (ε_{axial}(Z-direction)=-23% [averaged between the two heating rates $\Delta T/\Delta t$]). The effect of gravity cannot solely explain the results, because of the horizontal orientation inside the pushrod dilatometer.

The binder jetted FSLA material in this study was shown to behave anisotropically with the chosen process parameters. Therefore, the CAD scaling factors during the BJT build must be adjusted depending on the build direction in order to guarantee a good shape accuracy of the final components after sintering. However, due to this research and the deep understanding of the sintering kinetics it was possible to improve the sintering response significantly. With the help of two-step sintering profiles T(t), adjusted sintering plateaux and a suppressed grain coarsening much better results can be obtained.

"The binder jetted FSLA material in this study was shown to behave anisotropically with the chosen process parameters. Therefore, the CAD scaling factors during the BJT build must be adjusted depending on the build direction in order to guarantee a good shape accuracy of the final components after sintering."

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The rise of filament-based metal AM: New materials and machines present opportunities for MIM producers

BASF's Catamold® feedstock for Metal Injection Moulding triggered the massive expansion of the global MIM industry in the 1990s. With the same technology now adapted for filament-based metal Additive Manufacturing, and a new generation of Material Extrusion machines tailored to support what is widely known as metal Fused Filament Fabrication (FFF), can the same success be repeated? Andrea Gasperini, Ultimaker BV, Tobias Rödlmeier, BASF Forward AM, and Steve Cox, Amfori Consulting, consider the opportunities.

The readiness level and adoption of metal filament-based Material Extrusion (MEX), more widely known by the non-ISO/ASTM 52900 term of Fused Filament Fabrication (FFF), has increased considerably in recent years. With its low cost of entry and compatibility with the well-established debinding and sintering processes used in Metal Injection Moulding for decades, filament-based MEX could serve as a new string in the bow of MIM producers worldwide, enabling access to the low-volume, high-value applications previously outside of this industry's remit.

The most widely known metal Additive Manufacturing processes are Laser and Electron Beam Powder Bed Fusion (PBF-LB and PBF-EB, respectively), in which powders are added to a build plate layer by layer and melted using either a high-energy laser or electron beam to manufacture the part in one 'build' stage, after which excess unconsolidated powder is removed. The barrier to entry using these AM technologies remains high in terms of initial capital expenditure for the equipment, the required infrastructure and skills needed to operate, and the required maintenance to keep the systems running. These factors and more have turned away many potential users who could have benefitted from metal Additive Manufacturing, but were only exposed to PBF processes as a solution.

Meanwhile, sinter-based AM technologies such as Binder Jetting (BJT), Vat Photopolymerisation (VPP) processes, and – more recently – MEX-based processes are emerging as valid and lower-cost alternatives for metal and ceramic parts production. These processes may require an overall longer manufacturing

Fig. 1 Examples of additively manufactured and surface finished MEX parts produced with the Ultimaker S5

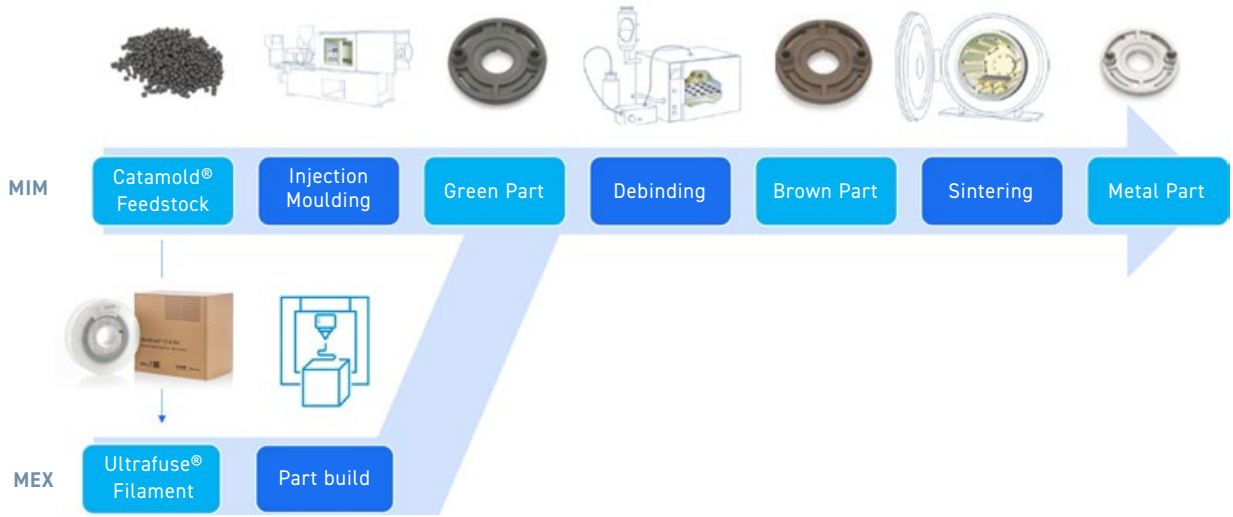


Fig. 2 Comparison between MIM using the market leading Catamold feedstock and filament-based MEX process steps toward a finished sintered part

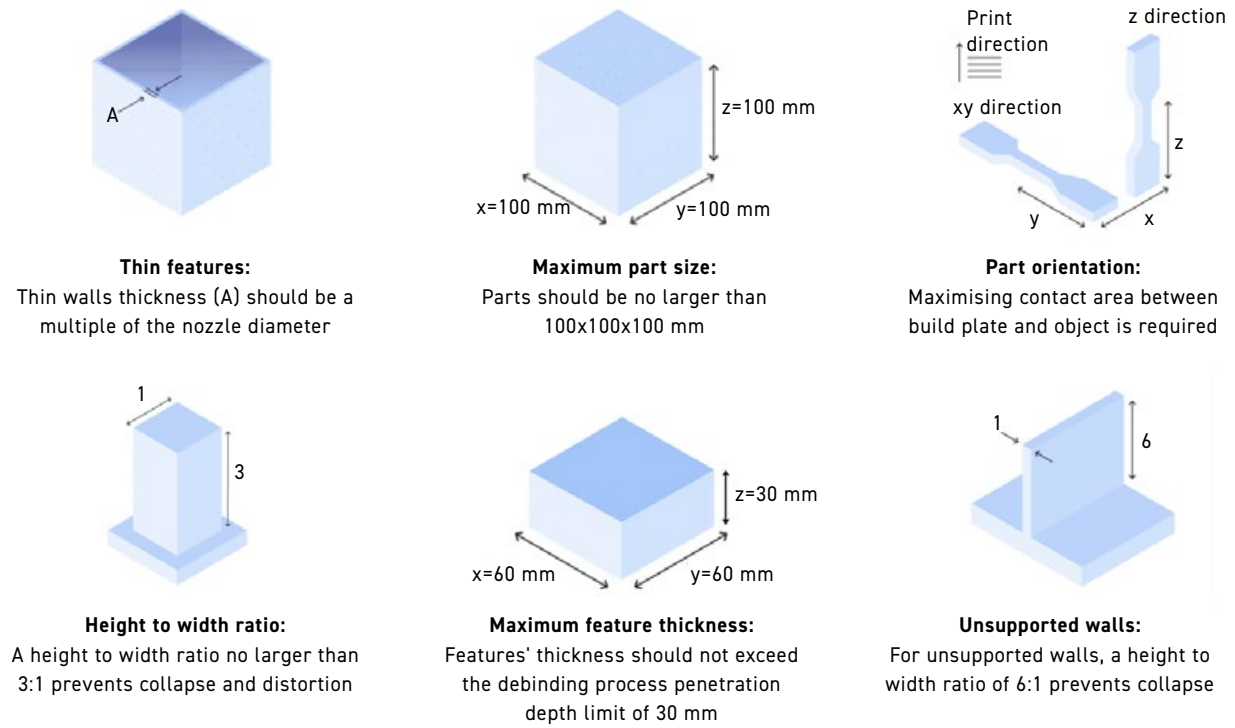
time to produce a solid part, but, compared to other metal AM options, filament-based MEX has a very low cost of entry (just over €1,000, if you already have a compatible desktop AM machine) and comes with no significant health and safety considerations, while providing a high-value return. The filament-based MEX process combines the geometric versatility of polymer moulding with the standard final part properties that can be achieved by the MIM process, by enabling producers to make metal parts using direct, layer-by-layer extrusion of metal-polymer filament through a heated nozzle.

The filament-based MEX process can be considered the closest Additive Manufacturing counterpart to the Metal Injection Moulding process. In both processes, similar feedstocks are extruded, either into a mould in the MIM process or via a heated nozzle in a filament-based MEX AM machine, to form a green part. In filament-based MEX, highly loaded thermoplastic filaments made of modified MIM feedstock pellets (e.g., BASF Catamold®) in different filament diameters (normally 1.75 or 2.85 mm) are fed into the filament-based MEX machine's print head. The use of thermoplastic binders makes the stainless steel powders flowable and compatible with the continuous extrusion process used in filament-based MEX.

The second step involves debinding the additively manufactured green parts. Depending on the type of binder, parts can go via the catalytical route (as for BASF Catamold), solvent debinding, or thermal debinding. With different process conditions, timing, and limitations, all these debinding routes aim to strip out most of the thermoplastic binder from the green part while maintaining sufficient structural stability in the newly formed brown part. Once about 80% of these organic materials are removed, the result is ready for sintering; this is where the last organic materials present in the brown part are completely removed. The remaining stainless steel powder is heated to over 1,300°C and the powder begins to solidify by various diffusional processes.

As expected, the result is volumetric contraction and a clean metal part with industry-standardised quality. Similar to the MIM process, users need to consider technology-related limitations that apply to the filament-based MEX process to guarantee a high-quality final part. Fig. 3 describes the most important design principles for filament-based MEX.

"The filament-based MEX process combines the geometric versatility of polymer moulding with the standard final part properties that can be achieved by the MIM process, by enabling producers to make metal parts using direct, layer-by-layer extrusion of metal-polymer filament through a heated nozzle."



Thin features:
Thin walls thickness (A) should be a multiple of the nozzle diameter

Maximum part size:
Parts should be no larger than 100x100x100 mm

Part orientation:
Maximising contact area between build plate and object is required

Height to width ratio:
A height to width ratio no larger than 3:1 prevents collapse and distortion

Maximum feature thickness:
Features' thickness should not exceed the debinding process penetration depth limit of 30 mm

Unsupported walls:
For unsupported walls, a height to width ratio of 6:1 prevents collapse

Fig. 3 Key design principles for filament-based MEX

Freedom of design with filament-based MEX

17-4PH stainless steel parts additively manufactured with the Ultimaker Metal Expansion Kit using BASF Forward AM's Ultrafuse® 17-4 PH filaments (Fig. 4), when debound and sintered through Ultimaker's network of debinding and sintering service providers, offer the desired martensitic properties that this material is known for. These excellent mechanical properties and good corrosion resistance make it one of the most popular and versatile metal materials in manufacturing. After sintering, parts feature similar characteristics to traditionally manufactured parts. As shown in Table 1, the filament-based MEX sintered specimen shows comparable mechanical properties to CNC parts. The data also shows that filament-based MEX manufactured parts have density values in the same range as the traditional values obtained via MIM.

Given the expected standard elemental composition of 17-4PH stainless steel, filament-based MEX produced parts can be further processed to achieve higher mechanical properties through standard solution annealing and hardening, (for example, with H900 heat treatment). Via these standard hardening processes, 17-4 PH parts produced using filament-based MEX can achieve an ultimate strength value above 1.2 GPa, as well as a 20% increase in yield strength of and

Fig. 4 The Ultimaker Metal Expansion Kit featuring BASF Forward AM's Ultrafuse 17-4 PH and an Ultimaker S5 desktop Additive Manufacturing machine

	Filament-based MEX[1] (XY)	Filament-based MEX[2] (XY/ZX) | H900 (XY/ZX)	MIM[3]	CNC[4]
Ultimate Tensile Strength (MPa)	760	990/1004 | 1276/1319	790	896 - 990
Yield strength Rp 0.2 (MPa)	680	756/764 | 1109/1136	650	827 - 914
Elongation at break (%)	4	3.8–4.0 | 6.4-7.0	4	6 - 6.97
Young's modulus (GPa)	190-195	190-195 |197-202	190-200	197 - 207
Hardness (HV10)	257	291 | 426		250 - 260
Carbon concentration	< 0.03%	< 0.03%	< 0.03%	< 0.03%
Average density	> 96% of Bulk	> 96% of Bulk	98.08% of Bulk	99.99%
DIN ISO	Stainless Steel 17-4 PH 1.4542 X5CrNiCuNb16-4	Stainless Steel 17-4 PH 1.4542 X5CrNiCuNb16-4	Stainless Steel 17-4 PH 1.4542 X5CrNiCuNb16-4	Stainless Steel 17-4 PH 1.4542 X5CrNiCuNb16-4

[1] Filament-based MEX: Ultrafuse 17-4PH TDS (Numbers refer to additively manufactured dogbones)

[2] Filament-based MEX: Ultrafuse17-4PH TDS (Numbers refer to additively manufactured, cut samples. Hardening according to H900 heat treatment method)

[3] MIM: Catamold 17-4PH TDS

[4] CNC: Hubs

Table 1 Reported properties of 17-4PH samples produced via filament-based MEX, MIM, and CNC

40% increase in hardness. However, the hardening process introduces a trade-off between superior mechanical performance and reduced corrosion resistance. Indeed, H900 hardening treatment on the as-sintered specimens is expected to increase brittleness.

17-4PH's properties come from its microstructure, as well as its nickel and chromium content which serve as the source of corrosion resistance. Therefore, a clean debind and sinter process ensures low carbon uptake and guarantees the right elemental composition without introducing undesired carbide additions or microstructural defects. Parts built using BASF Ultrafuse 17-4PH, followed by industrial-standard debinding and sintering, are ideal for applications that need to withstand the highest possible mechanical properties and have a medium-high corrosion resistance.

When most people think of metal Additive Manufacturing, high-value, high-performance applications come to mind. These are typically produced using a more established technology such as Laser Beam Powder Bed Fusion. Whilst these parts can achieve extremely tight tolerances, high density levels, and large sizes, a high capital and operating costs have limited the market to sectors such as aerospace, energy, and medical.

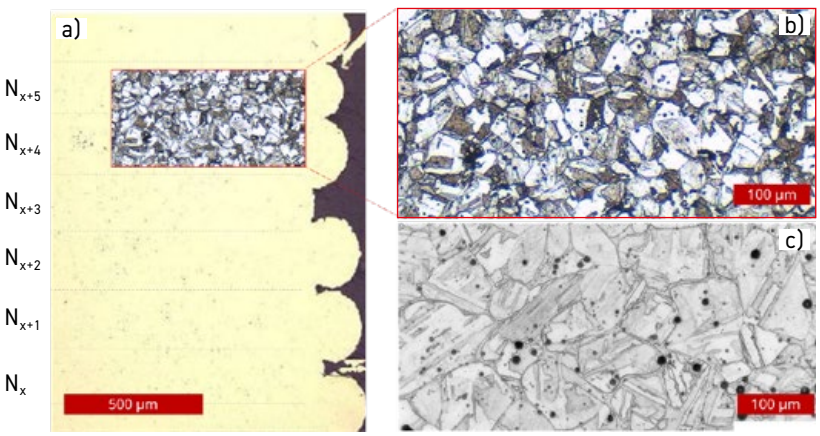


Fig. 5 a) Cross section of an filament-based MEX manufactured 17-4PH part, b) grain microstructure of a sintered part using Ultrafuse 17-4 PH filaments and c) grain microstructure of a sintered MIM part using Catamold 17-4 PH pellets

In contrast, the ideal entry-level applications for filament-based MEX include many custom auxiliary components that cannot be bought off the shelf. Several global filament-based MEX adopters are already implementing additively manufactured parts in their operations using Ultimaker machines. As shown in Fig. 5, the current application sweet spot comprises small functional prototypes, customised tools and fixtures, small series of slow-moving, high-MOQ (minimum order requirement) parts, and some plastic replacements in high-load and/or temperature-resistance environments. On their own, these components may be of lower value compared to the type of parts that are currently sourced via other Additive Manufacturing technologies or CNC, but their multiplicity and wide-ranging potential makes filament-based MEX an equally profitable technology.

Indeed, filament-based MEX can play a pivotal role as a complementary technology to CNC and MIM when it comes to producing small volumes of complex, customised parts that have features more suitable to be built additively at no additional effort or cost. This is true for complex features that would require a high amount of preparation effort on a multi-axis CNC machine and especially true when order volumes and material waste are considered. Indeed, compared to CNC milling and MIM, filament-based MEX can bring additional design freedom and functionalities at no additional cost, such as:

- Interlocked assemblies
- Organic shapes via generative design
- Embedded features such as cooling channels

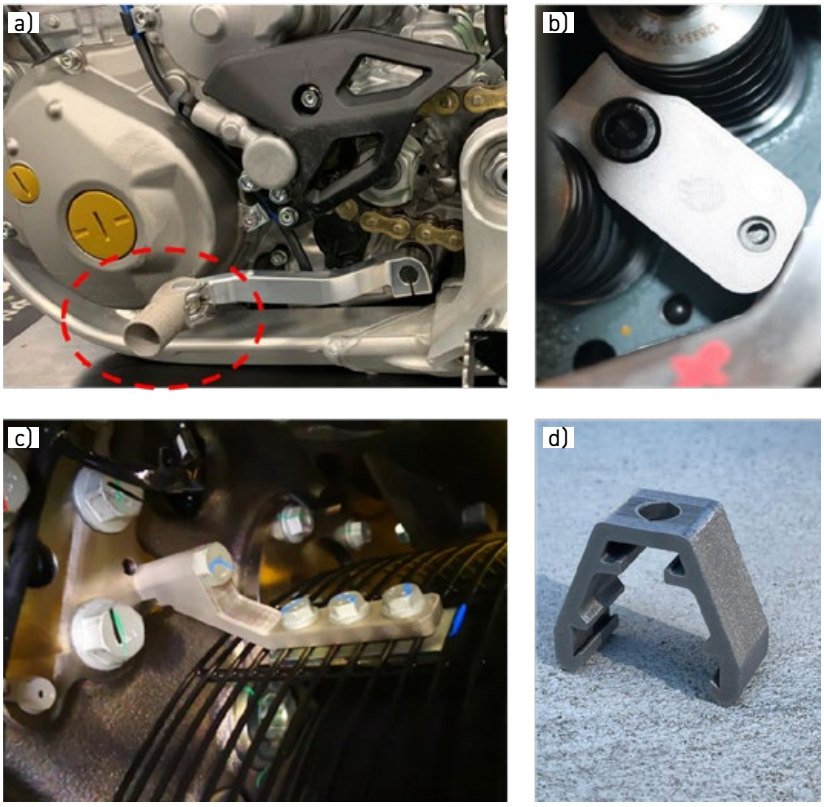


Fig. 6 In-use additively manufactured metal parts produced via filament-based MEX from a) Kawasaki, shift level mount, b) Liebherr Components Colmar SAS, assembly tool, c) Liebherr Components Colmar SAS, fan bracket, d) Sparox Wien Energy, PV panels mount

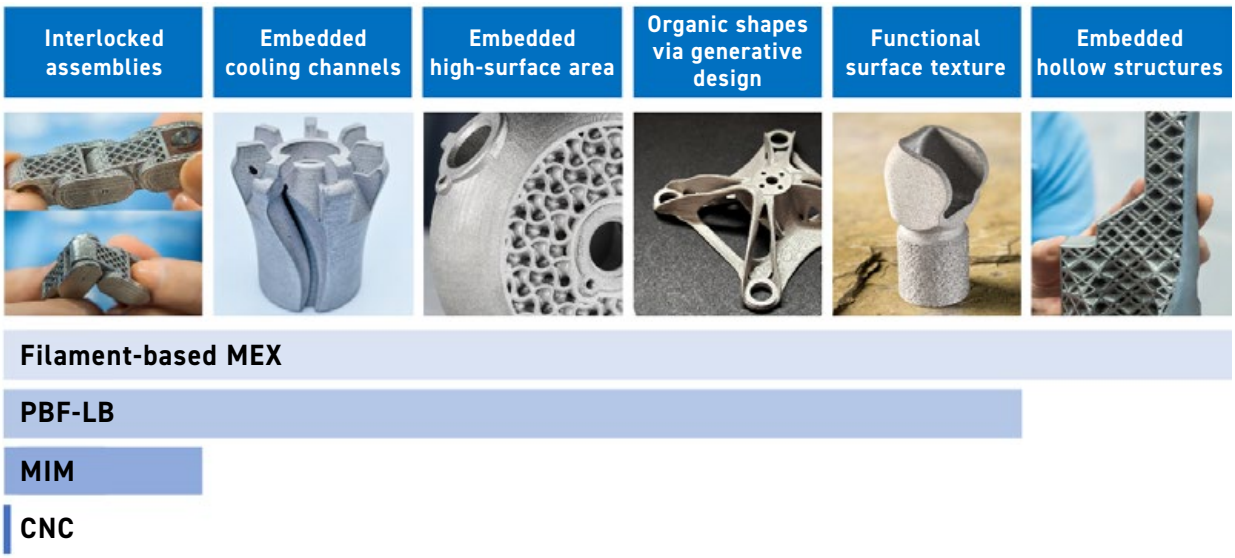


Fig. 7 Freedom of design comparison between filament-based MEX, PBF-LB, MIM and CNC

Fig. 8 Sintering filament-based MEX additively manufactured parts at Elnik Systems GmbH

- Functional surface textures
- High surface area geometries

Unlike PBF-LB, filament-based MEX can also be used to create closed hollow structures – particularly useful for lightweighting.

New opportunities for established debinding and sintering experts

The adoption of filament-based MEX is now on an accelerated path thanks to the year-over-year increase in readiness levels, boosting adoption and awareness of the technology in the AM community. A clear indicator of this acceleration is the wider public's endorsement of metal filament-based MEX from a number of Additive Manufacturing machine makers. This started with Markforged and Desktop Metal, and was followed last year by others, including Ultimaker, BCN3D, Raise3D, and 3Dgence.

The metal filament-based MEX proposition is fuelled by the arrival of new materials to the market from an increasing number of filament manufacturers. BASF Forward AM began this trend, and many others have followed suit in the recent year. However, unlike Markforged and Desktop Metal, not all AM manufacturers rely on end-to-end solutions that include debinding and sintering equipment. Instead, a new ecosystem is developing to fulfil these post-processing steps.

Several established debind and sinter equipment manufacturers are increasingly stepping into the AM world with specific and targeted products that meet the lower volumes of filament-based MEX parts producers and have more compact footprints, such as Xerion Berlin GMBH with its Xerion Factory solution, and deliver access to an open system not dependent on one supplier.

Elnik Systems and DSH Technologies have also partnered with BASF Forward AM to pioneer on-demand debinding and sintering services for the user community interested in post-processing green parts without the need to source and run the processes in house. To facilitate broader adoption of filament-based MEX, they have recently developed a centralised network of service partners to utilise large equipment for cost-effective post-processing without having to sacrifice quality. This makes available post-processing from companies with decades of experience, in an industrial-quality environment, enabling the most competitive alternative to full in-house solutions on the market.

The use of this debind and sinter network is today the most accessible way for users to insource part production. Doing so requires minimal investment - only an Ultimaker machine and Metal Expansion Kit - to try the workflow. Today, access to the network has been further simplified in terms of logistics and ease of use for both users and debinding and sintering service providers thanks to the recently launched BASF Forward AM debinding and sintering order management portal. This portal allows customers to create a service order digitally and follow the operations and status of their parts live while they are processed at the partner facility, providing real-time information and maximum transparency over handling and timelines.

CMG Technologies, UK, serves as a successful example of how a company can translate in-house expertise in PIM into a new range of local and professional services. Without further investments in equipment

Fig. 9 Low-volume series of custom spray adaptors in 17-4PH built using filament-based MEX by the service bureau Sculpteo

or knowledge, the company can now fulfil the growing needs of the AM community's filament-based MEX userbase. The synergy between the current expertise and increasing demand from the AM community to connect with professionals and local services represents a real opportunity for MIM houses to engage in new developments and projects with a new customer base.

While filament-based MEX adoption within MIM houses is slow to advance further than simple prototyping or tooling for their existing customer base, the AM market's demands point strongly towards low volumes of new, complex, locally produced low-cost metal parts.

It should also be considered that the AM community's different expectations of surface quality versus MIM standards are well accepted in this specific application sweet spot. This is in exchange for a drastically higher design freedom, an unusually low total cost of ownership, and the up-to 90% achievable savings on small series of custom tools and auxiliary components.

MIM houses can therefore play a pivotal role in delivering local production of those type of metal parts that the AM community is increasingly demanding. Recognising AM's opportunities would allow MIM houses to become, at almost no additional investment, an important service hub for AM metal applications.

Up to 90% cost savings: Spray painting adaptor case study

As previously mentioned, on top of the increased design freedom unlocked by filament-based MEX, low volumes of custom parts produced by filament-based MEX can be 3–10X cheaper than those produced by traditional milling and turning machines or other Additive Manufacturing processes. To demonstrate this, we compared the cost per unit and lead times to produce these custom spray paint flow adaptors across different technologies. For traditional metal machining and AM technologies, a series of quotes for three units in 17-4 PH were requested from different external providers around the world. For filament-based MEX, the component's size (47 x 31 x 31 mm) and weight (75 g) fit well within the limitations of the in-house process.

As shown in Table 2, parts produced in-house using Ultimaker's Metal Expansion Kit

"While filament-based MEX adoption within MIM houses is slow to advance further than simple prototyping or tooling for their existing customer base, the AM market's demands point strongly towards low volumes of new, complex, locally produced low-cost metal parts."

Option	Service provider	Country	Manufacturing technology	Unit price	Total price	Part leadtime	Quote leadtime	Total costs vs Option 1	Filament-based MEX savings (%) vs other options
1	In-house	Netherlands	Filament-based MEX	€28.30	€84.90	15 days	-	-	-
2	Sculpteo	online	Filament-based MEX	€42.82	€128.46	17 days	-	+ €43.56	34%
3	Protolabs	online	PBF-LB	€116.00	€346.26	15 days	-	+ €261.36	75%
4	Protolabs	online	CNC	€541.00	€1153.26	21 days	-	+ €1,068.36	93%
5	Xometry	online	PBF-LB	€171.50	€513.00	19 days	-	+ €428.10	83%
6	Xometry	online	CNC	€162.50	€487.00	27 days	-	+ €402.10	83%
7	3Dhubs	online	CNC	€181.00	€181.00	23 days	-	+ €96.10	53%
8	workshop	Germany	CNC	€99.00	€297.00	20-25 days	2 days	+ €212.10	71%
9	workshop	US	CNC	$200.00	$600.00	20 days	2 days	+ $515.10	86%
10	workshop	Netherlands	CNC	€316.00	€948.00	20 days	6 days	+ €863.10	91%

Table 2 Comparative prices and lead times of the different options quoted

offered a unit price 62% lower than the next best alternative. Compared to other manufacturing technologies, in-house production yielded cost savings of 85% when compared to the cheapest CNC workshop offer and up to 95% when compared to the same parts produced using PBF-LB at Protolabs. Interestingly, lead times with in-house production remain in line with the current estimated lead time from both online workshops and local ones.

To fully assess the surface quality of the filament-based MEX manufactured and sintered spray adaptor produced using the Ultimaker S5 and the Ultimaker Metal Expansion Kit, a high-resolution scan analysis for a selected number of AM parts on GOM ATOS Core 3D scanner was performed. Fig. 10 shows a colour-map surface comparison between the CAD file and the cloud point data

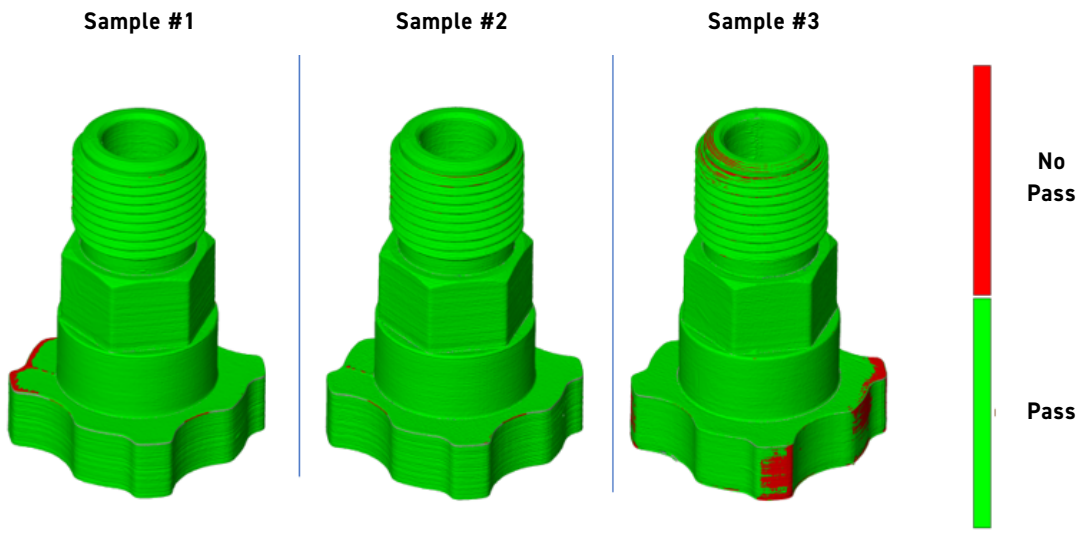


Fig. 10 Colour-map surface comparison between CAD file and cloud point data resulting from the scanning of the object for all three technologies

resulting from the scanning of the object. This colour map was generated through a pass/no pass filter with a selected threshold of ± 0.3 mm. This highlights the relative deviations between the ideal model (CAD) and the actual scanned part (cloud points obtained from scanning the physical item). The two sets of data have aligned one relative to the other by minimising the overall sum of the squared distance of each pair of points (minimum quadratic error).

To visually correlate colours with surface points' deviations, green was chosen to indicate points that still fall within the assigned threshold, whereas red points on the surface do not. From the colour map in Fig.10, it is possible to see that more than 99% of the points for sample 1 and 2, and more than 95% of the surface of scanned sample 3, fall within the tolerance range of ± 0.3 mm. As for the out-of-tolerance area (red) present at the base of the object, this does not impact its usability given this area's lower relevance within the working adaptor assembly.

Fig. 11 Set of small series of green parts ready for sintering at Elnik Systems GmbH

Outlook

The field of filament-based MEX has advanced enormously since the 2019 launch of BASF's Forward AM Ultrafuse filaments. Their introduction ushered in a range of benefits for a growing user base – spanning from near-net shape metal parts to bulk-like mechanical performances. These are now achievable on a desktop filament-based MEX machine, like the Ultimaker S5, for a total investment of less than €8,000.

The proof of this wider adoption is visible in the serious and public endorsement of more and more AM machine makers officially supporting filament-based MEX capabilities on their platforms. Driven by this strong OEM-led initiative, an entire filament-based MEX ecosystem is developing today where more users, material manufacturers, furnace manufacturers, and simulation software providers are providing targeted solutions for the growing filament-based MEX user base and their needs.

Professional and local debinding and sintering service providers are adding to the momentum; they guarantee to their filament-based MEX customers near-net shape and high-purity grade final metal parts. Among these, Elnik Systems GmbH, DSH Technologies, and CMG technologies have in recent years shown the way for more MIM houses to join this growing ecosystem – ready to deliver on the promise of more localised production of new, advanced, and low-cost metal parts.

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Sinter-based Additive Manufacturing at the 20th Plansee Seminar on Refractory Metals and Hard Materials

The hardmetals industry is well used to making high-performance components from metallic powders. Today it is an industry with global sales in excess of $15 billion and applications that range from cutting tool inserts to components for oil & gas, construction and beyond. The processing of hardmetals, otherwise known as cemented carbides, by Additive Manufacturing has inevitably become an area of intense activity, building, in part, on expertise from the industry's use of MIM to deliver greater design complexity. Bernard North reports on innovations in the sinter-based AM of hardmetals presented at this year's Plansee Seminar.

This year the Plansee Group continued its long tradition of holding a week-long technical seminar on refractory metals and hard materials at its headquarters near Reutte, in the beautiful Austrian Tyrol. Since 1977, the interval has been every four years, but, due to COVID-19, the 20th Plansee Seminar was delayed from 2021 to 2022. A broad range of subjects was covered by very detailed technical presentations and posters, making this a wonderful event where many of the technical leaders in the industry and associated academia get together for an in-depth exchange of information. For an overview of the entire seminar, see this author's recent article in the Autumn 2022 issue of *Powder Metallurgy Review*.

In recent years, the range of subjects covered at the Plansee Seminar has broadened to include Additive Manufacturing, and, indeed, about 15% of the overall content in 2022 was on Additive Manufacturing. These presentations and posters may be split by process type into three categories. The first such category covers Powder Bed Fusion (PBF) processes, whereby an energy source, most commonly a laser (PBF-LB) or electron beam (PBF-EB) melts a powder bed into dense parts 'in situ.' Here, the focus is primarily on refractory metals.

The second process type can broadly be referred to as sinter-based Additive Manufacturing, also referred to as indirect Additive Manufacturing, in which a 'green' part is formed by an AM process and is then conventionally debound and sintered in a route that is very familiar to those in the Powder Injection Moulding (PIM) industry. Sinter-based AM processes appear to be primarily focused on cemented carbides – also known as hardmetals.

The third type of AM process covered at the 2022 Plansee Seminar was Cold Spray, in which powder

Fig. 1 The Plansee Seminar 2022 was once again held at the Plansee Group's headquarters near Reutte, in the Austrian Tyrol (Courtesy Plansee Group)

Forming process	Minimising shrinkage during sintering?	Need precision tooling?	Part surface finish?	Complexity possible?	Green machining necessary?	Thick -walled part capability?	Thin-walled part capability?	Internal detail capability?	Wide range of grades?
Uniaxial pressing									
Wet bag isostatic pressing									
Dry bag isostatic pressing *									
Extrusion **									
Powder Injection Moulding									
Biaxial or triaxial 'side' pressing									
Green part + sinter Additive Manufacturing									

** Axially symmetric shapes usually*
*** Axially symmetric shapes only*

Table 1 Overview of cemented carbide shaping technologies

is propelled at high speed and impacted on a mandrel. The first and third categories will be covered by an upcoming article in *Metal Additive Manufacturing* magazine, while the second is the subject of the present article.

Some background on the forming of cemented carbide parts

Table 1 lists the various processes used to create cemented carbide green parts in approximate date order of their commercialisation. The term 'green' refers to a shape that consists of powders, either combined with a polymeric binder or compacted under high pressure prior to sintering to form a dense component. Several shaping processes are in use, each with its own strengths and limitations. The correct process will be selected based on the geometry and anticipated production volume of the respective parts.

In practice, many components require one or more post-sintering shaping steps, most commonly abrasive grinding, but also electrical discharge or laser machining. Due to cost, these steps are usually avoided or minimised unless absolutely necessary.

For the more complex geometries, the three main processes to form a green part are Cold Isostatic Pressing (CIP) followed by green machining, Powder Injection Moulding (PIM), and biaxial or triaxial pressing. All three are very capable of making complex parts in a full range of hardmetal grades, but the first requires precision green machining after making a simple green blank, while the second and third both require expensive, high-precision, wear-resistant die or mould tooling with often complex actuation mechanisms, and are thus usually only justified by high production quantities of a specific geometry hardmetal component.

Once Additive Manufacturing appeared on the development scene it was inevitable that it would be applied to cemented carbides, firstly because AM processes obviate the need for tooling and secondly for the extra design freedom they afford, including the ability to make complex internal geometries or cavities which the existing processes could not – economically, at least – make. An excellent overview of this effort was authored by Pötschke [1].

In summary, the most widely known metal AM process, PBF-LB, works poorly for cemented carbides due to very high local heating giving undesirable microstructures and/or cracked parts, although the PBF-EB process has been successfully used for high Co, WC-CrC materials [2]. Most work in the field, however, has been on processes whereby a green part is formed and then conventionally debound and sintered. Per [1], the main processes are Binder Jetting (BJT), whereby a layer of pre-sintered WC-Co powder is selectively bonded into a part with the application of an organic binder, and filament-based Material Extrusion (MEX), also known as Fused Filament Fabrication (FFF), whereby a fine 'thread' of feedstock is laid in a pattern to form a green part.

The BJT process has the disadvantage of lower green density and resultant high shrinkage, propensity to distortion, and an effective limitation to more sinterable compositions with > ~12 wt.% Co, while the MEX process suffers from slower part build and debinding times. Process variants also exist, with one being

Lead Author	Organisation	Subject	Process Type
Norgren	Sandvik AB, Lund Univ	WC-12Co Varel nozzles	BJT
Cabrezas	University of Catalonia	WC-12Co microstructures and mechanical properties	BJT
Nigarura	GTP	Tungsten heavy metal	BJT
Wolfe	GTP	WC-10Co and WC-12Co. Microstructure, mechanical properties and example parts	BJT
Prichard	Kennametal	WC-10Co (submicron) process optimisation to reduce porosity and extend range of practical cabide compositions, end mill metalcutting test	BJT
Alves	University of Coimbra	Aimed at filament process - wetting studies on solid WC-Co	MEX
Faria	University of Aviero	Robocating/extrusion process - Si_3N_4	MEX
Kitzmantel	RHP	WC-12Co filaments made 'in situ' by screw extrusion process	MEX
Bose	Desktop Metal	WC-10Co filament process	MEX
German	University of San Diego	Microgravity heavy metal sintering of conventionally pressed powders, but with a view to future BJT or MEX processing in space	-
Carreño-Morelli	University of Western Switzerland	WC-12Co solvent on bound granule process, plus concrete drilling test	Solvent on granule
Pötschke	FhG IKTS Dresden	WC-12Co comparison of BJT, MEX and related 'direct ink writing'. EPMA consortium	Various
Gestrich	FhG IKTS Dresden	WC-9Co and WC-10Co using BJT, MEX and controls. Paper concentrates on debind and sinter	Various

Table 2 Overview of sinter-based AM presentations at the 20th Plansee Seminar

a 'solvent-on-granule' process whereby granules containing powder and binder are selectively bonded in a bed with a solvent that dissolves the organics in the granules and thus forms a green part.

A further process featured at the Plansee Seminar could also be considered as a Material Extrusion process, whereby a heavily powder-loaded suspension is directly 'printed' by a nozzle, also referred to by the paper's author as 'direct ink writing' and Robocasting.

Last year's presentations at the PowderMet 2021 conference, Orlando, USA, gave a 'snapshot in time' of progress in the field [3]. At that time, the emphasis was clearly on Binder Jetting, with two major hardmetals manufacturers marketing WC-17 wt.% Co compositions, and with published research on harder, more wear-resistant compositions with less Co – as low as 10 wt.% Co, albeit a coarse-grained composition where green densities are higher and grain growth due to 'over sintering' is less of a concern.

"Last year's presentations at the PowderMet 2021 conference, Orlando, USA, gave a 'snapshot in time' of progress in the field. At that time the emphasis was clearly on Binder Jetting, with two major machine manufacturers marketing WC-17 wt.% Co compositions..."

Presentations on the sinter-based AM of cemented carbides

Since most cemented carbides are in the range 5 to 11 wt.% Co, and many of them have a fine or submicron grain size, it is critical if AM is to be very widely applied in the hardmetal industry that processes be developed or further refined to handle such compositions, and this author, along with many colleagues, was excited to hear of progress in the field. Table 2 lists such contributions. There were thirteen contributions, of which eleven were on cemented carbides

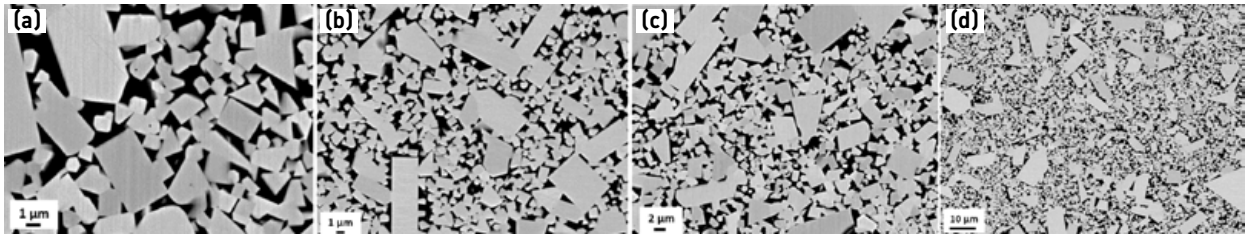

Fig. 2 Representative microstructure images at different magnifications: a) x 5000, b) x 3000, c) x 2000, and d) x 1000 [5]

(in most cases with 10 or 12 wt.% Co). Most were on the Binder Jetting or filament-based Material Extrusion processes, however there were also presentations on more niche AM processes and innovative variants, none of which should be overlooked in the fast-moving and innovative AM industry.

The Binder Jetting of cemented carbides

Susanne Norgren, Sandvik AB and Lund University, Sweden, as part of a wide-ranging invited talk, described WC-12 wt.% Co drilling coolant nozzles for a Varel cutter body used in the oil and gas industry [4]. The ability to customise designs, as well as reduce lead times and inventory, were mentioned as significant benefits.

Laura Cabezas, Universitat Politècnica de Catalunya, Spain, and co-authors described microscopy, as well as hardness (at different loads) and scratch testing on overpressure sintered (100 bar) medium/coarse grained WC-12 wt.% Co [5]. Due to low green densities, a high (1500°C) temperature was required to get full densification. The microstructures showed a marked bimodal grain size distribution due to the high sintering temperature, but measurements on different planes oriented with respect to the build direction, nozzle movement direction, and perpendicular to both indicated isotropy of microstructure and properties (Fig. 2). Future work is planned on non-bimodal WC-12 and 17 wt.% Co materials.

Thomas Wolfe, Global Tungsten & Powders Corp, USA, and co-authors discussed the microstructures, hardness, fracture toughness, transverse rupture strength, and wear testing of spray dried and pre-sintered ~20 µm spherical granules of WC 10, 12, and 17 wt.% Co, after Binder Jetting of 50 µm layers and pressure sintering at 1435–1485°C at either 18.3 bar or 50 bar [5]. Sintering shrinkage was relatively high (in the range 21 to 27% linear) with apparent density data on the granules suggesting shrinkage is less for coarser-grained materials.

In general, microstructures and mechanical properties are similar to conventionally processed comparisons, although the medium grain size materials show non-uniform microstructures associated with the higher sintering temperatures required to attain full density, which can affect wear resistance (positively) and strength (negatively). Images of AM parts were shown in medium and extra coarse WC-12 wt.% Co

Fig. 3 BJT parts made from WC721A12 and WC780A12. Clockwise from top left: Combination spur and helical gear, impeller, pinion, helical gear with integral dog clutch, pump impeller [6]

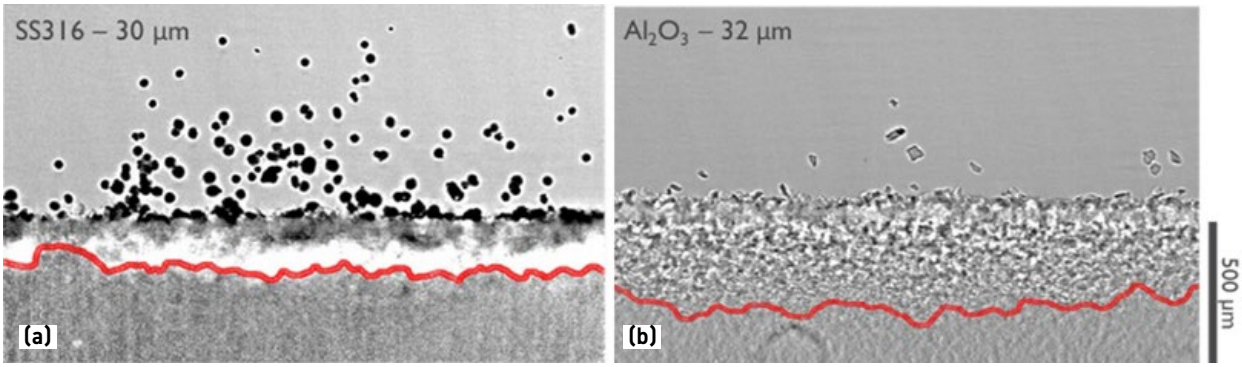

Fig. 4 High speed X-ray images of powder ejection and penetration in Binder Jetting for (a) 316L stainless steel powders and (b) alumina powders [7]

cemented carbide, one of them ~8 kg in weight (Fig. 3).

Paul Prichard, Kennametal Inc., USA, and co-authors reviewed literature on what happens during Binder Jetting in terms of the solvent/binder droplet impacting the powder bed (powder particles are ejected by the impact and then land elsewhere on the bed) and the subsequent infiltration of the binder solution into the powder bed, and how build parameters affect the degree of overlap of bonded powder layers (Fig. 4) [7]. He described a three-factor, two-level designed experiment using submicron WC-10 wt.% Co with varied granule size, jet orifice size, and bed depth, while keeping the solvent/binder, bed temperature, and saturation constant.

Sintering was performed in vacuum at 1480°C to clearly show sintered porosity, and it was apparent that both the porosity directionality reflected that of the Binder Jetting process, and that the size and quantity of porosity was strongly dependent on the input variables, especially granule size (finer better) (Figs. 5, 6). Prichard described an optimal granule type of intermediate size and broader size distribution with the best overall characteristics (with the exception of depowdering), and he showed a video, on pressure sintered (1440°C) material, of a tough end mill metalcutting test on AISI 4140 steel, demonstrating equivalent performance to conventionally produced tools (Fig. 7).

Salvator Nigarura, Global Tungsten & Powders, USA, and co-authors from Tikomet Oy, Finland, presented a

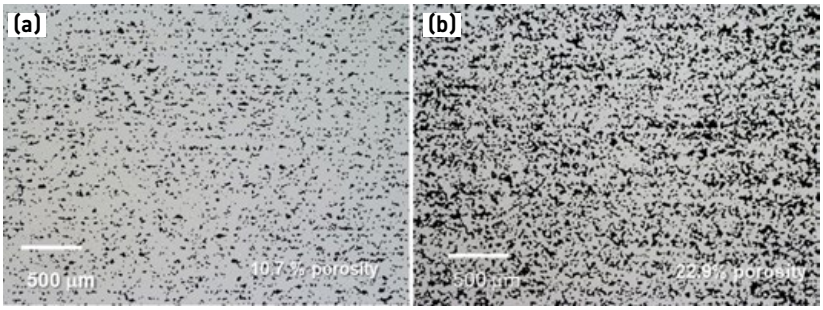

Fig. 5 Vacuum sintered at 1480°C porosity developed with (a) fine powders (D50 = 15 mm) and (b) standard powder (D50 = 30 mm) [7]

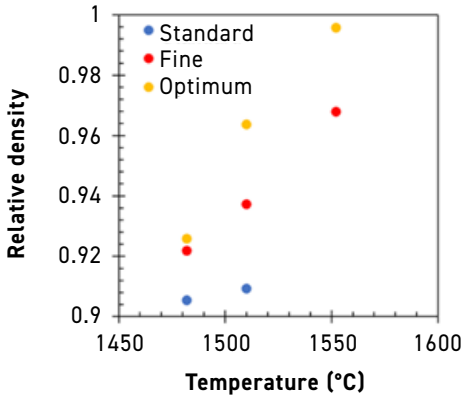

Fig. 6 Sinter HIP Densification of WC-10Co with various PSD and temperature

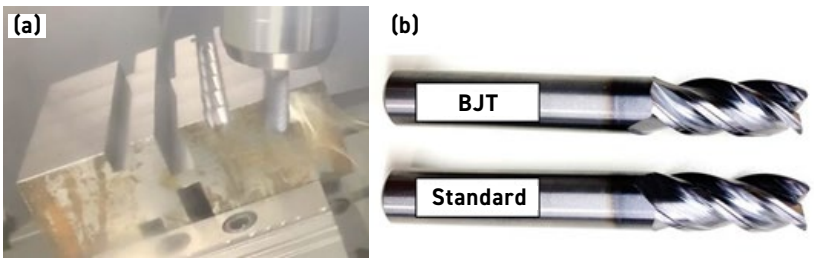

Fig. 7 BJT WC-10Co Kennametal Harvi1 TETM endmill 5-axis cutting 4140 steel (30 HRc). (a) Initial full slot 2D endmill, (b) Standard tool Harvi1 TETM tool geometry [7]

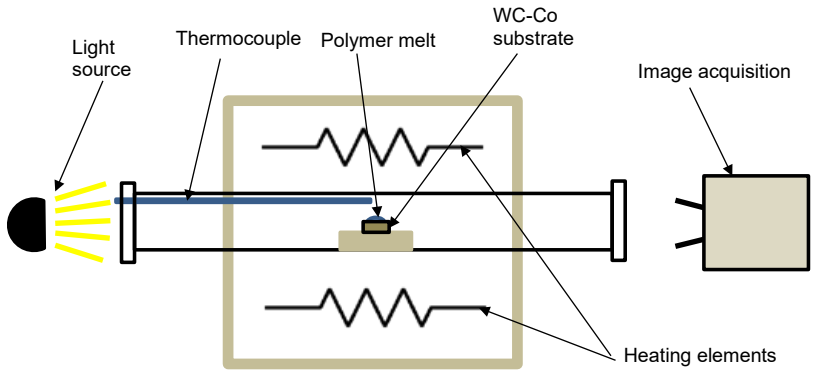

Fig. 8 Scheme of the setup used for wettability testing [10]

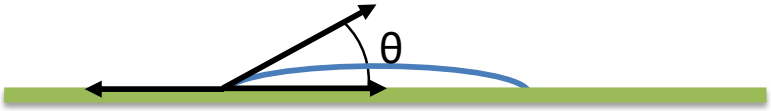

Fig. 9 Scheme of contact angle (θ) measurement [10]

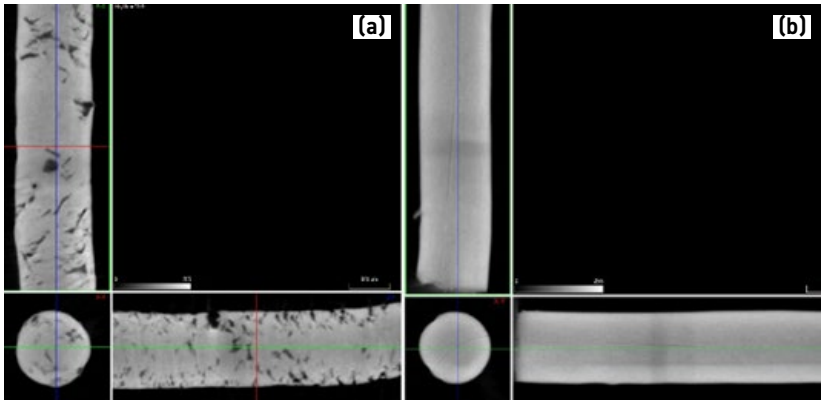

Fig. 10 Microtomographies of WC-Co based filaments with different binder a) with internal defects and, b) without defects [10]

paper on the Binder Jetting of 92-94 wt.% tungsten heavy alloys with a Ni + Fe binder metal [8]. Compared to the normal plasma-densified powder, a recently developed powder with a far less spherical morphology, and with binder metal-rich surfaces, gave substantial improvements in both green and pre-sintered strength, and allowed high-quality material to be manufactured at conventional sintering temperature. These improvements should greatly ease the adoption of Additive Manufacturing of tungsten heavy alloys.

The 'solvent-on-granule' process

Efraín Carreño-Morelli, University of Applied Sciences and Arts Western Switzerland, and Steven Mosely, Hilti Corp, Liechtenstein, described a significant variant of the Binder Jetting process, whereby the powder granules are bonded with organics rather than being pre-sintered, and the jetted droplets are of solvent only [9]. Claimed advantages for the process include higher green density and green strength, easier depowdering, and better part dimensional control. The granules are smaller than conventional cemented carbide, and may be made by spray drying, or granulation plus sieving. WC with 10 or 12 wt.% Co was made into granules with 15 and 20 vol.% thermoplastic binder and then bonded with an aqueous/alcohol solvent.

Green densities of 40% theoretical were obtained and vacuum sintering resulted in ~97% dense material; subsequent Hot Isostatic Pressing (HIP) resulted in close to theoretical density (albeit with some Co binder 'pools'). Dimensional control was good and parts were brazed to steel holders and concrete drilling testing performed, although, for this application, a lower (6–9 wt.%) Co level is required for best performance.

Material Extrusion for cemented carbide production

B Alves, University of Coimbra, and co-authors from Palbit S.A. and University of Aveiro, Portugal, described work to pre-select organic binders for the filament-based Material Extrusion process in order to reduce porosity and flaws, as well as reduce debinding times [10]. They used image acquisition and analysis to measure the contact angle of five different organic lubricants on a polished cemented carbide surface in the temperature range 150–220°C (Figs. 8-10). Table 3 summarises the characteristics of the selected properties.

Smaller contact angles indicate good wetting, which is a critical characteristic of a good binder. Initial analysis indicates polypropylene and polyoxymethylene have the best wetting behaviour, however work on mixed organics needs to be done to determine more optimised binders. The authors also described early work using X-ray micro-computed tomography to look at compositional homogeneity in filament feedstock – WC and Co powders may de-mix during powder processing, and it is important to minimise that phenomenon.

Michael Kitzmantel, RHP-Technology GmbH, Austria, and co-authors emphasised the synergy between filament-based MEX and Metal Injection Moulding, with the suggestion that the former functioned as a rapid prototyping process for the latter, as well as being able to use feedstocks intended for MIM [11]. The authors described the creation of 55 vol.% solids filaments through heated screw extrusion of pelletised WC-12 wt.% Co feedstock around 30 µm in diameter being used to make test coupons, as well as an 'octopus' demonstration part – they also plan to make an M6 bolt.

A two-step (solvent, then thermal) debinding process is employed. Vacuum sintering results in only 95-98% density with low hardness, but pressure sintering resulted in dense material with Vickers hardness (10 kg load) of 1626 kg/mm^2 and K1c of 9.7 MPam$^{1/2}$. The presentation stressed the advantage of the process for making parts with internal cooling channels, and with predictable (albeit anisotropic) shrinkage, but having surface finish inferior to that of MIM parts.

Animesh Bose, Desktop Metal, and co-authors from Global Tungsten & Powders and MiRus, USA, gave a very detailed description of Desktop Metal's filament-based MEX process in general, and described recent work on WC-10 wt.% medium grain size cemented carbides produced on the company's Studio system (Figs. 11 and 12) [12]. The paper stressed the process and part design synergies with MIM. A planetary mixer was used to intimately blend the WC-Co powder at a 45 vol.% level with a multicomponent organic lubricant, and 150 mm long, 6 mm diameter feedstock rods were made for the cartridge used to feed the AM process. Material was extruded at 160°C through a 400 µm nozzle at 15 mm/sec and a 150 µm layer height to form test pieces and parts of various shapes. The 'base' of components and the components themselves were separated by an inert ceramic layer, also deposited by the MEX process.

Polymer	Density	Glass transition temperature (°C)	Melt temperature (°C)	Crystallinity
HDPE	0.950	-100	130	High
LDPE	0.904	-100	110	Medium
POM	1.420	-13	178	High
PP	0.900	-25	170	Medium
PLA	1.240	60	170	Low

Table 3 Summary of the characteristics of the selected properties [10]

"Michael Kitzmantel, RHP-Technology GmbH, Austria, and co-authors emphasised the synergy between filament-based MEX and MIM, with the suggestion that the former functioned as a rapid prototyping process for the latter..."

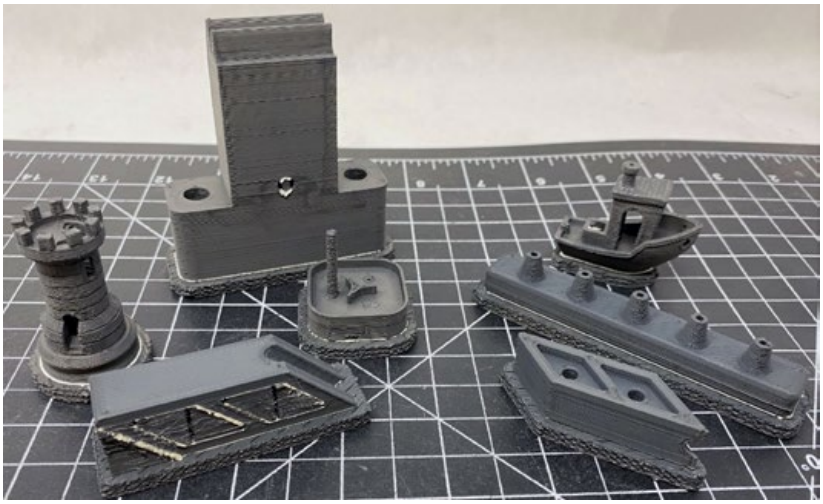

Fig. 11 Several examples of tungsten carbide parts produced on Desktop Metal's Studio machine, in the as-built state [12]

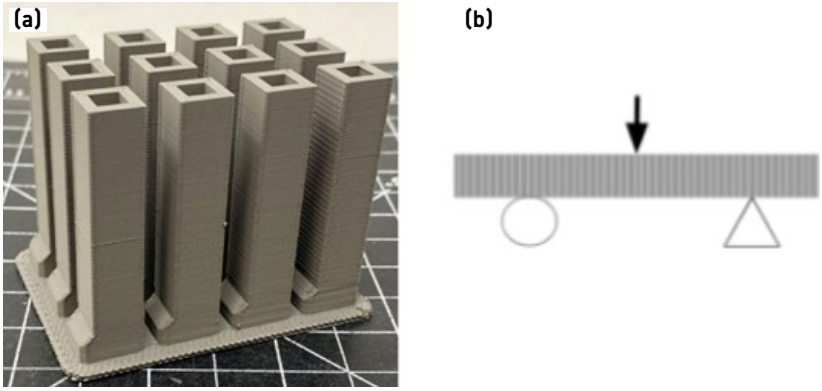

Fig. 12 a) As-built layer adhesion strength samples (set of 12); b) Illustration of the 3-point bending setup for testing the hollow rectangle specimens [12]

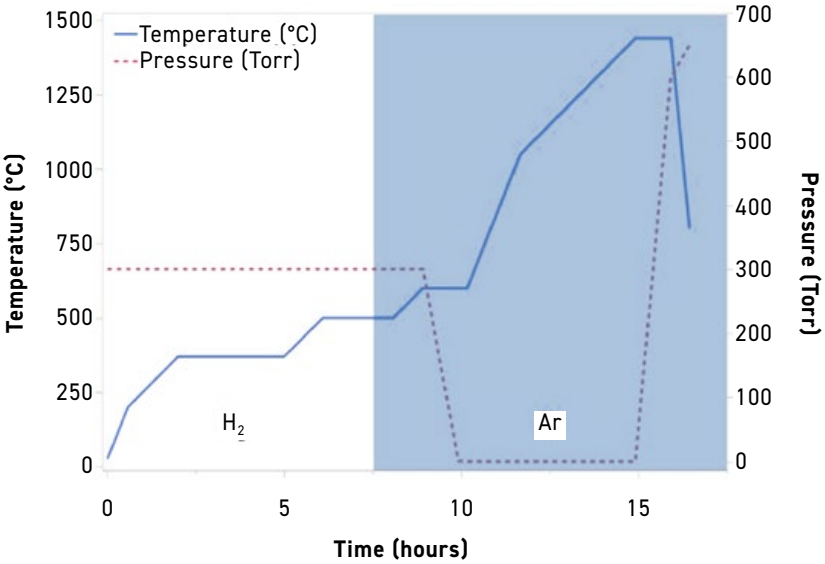

Fig. 13 Temperature, pressure profile, and sweep gases used for vacuum sintering of the carbide parts [12]

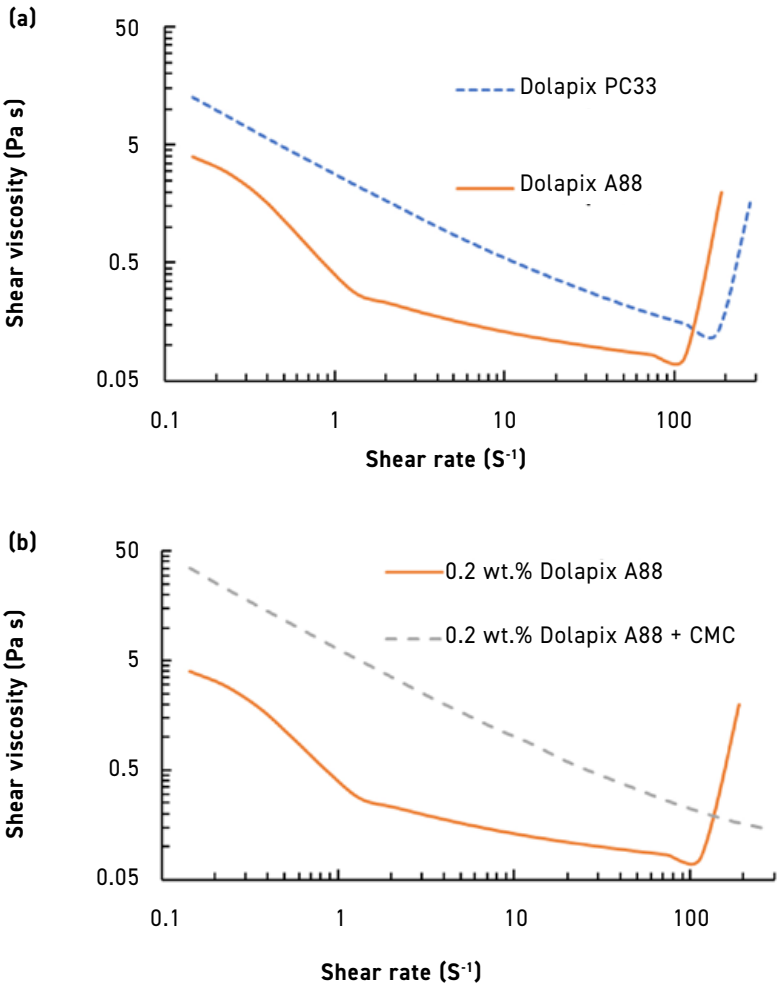

Fig. 14 Viscosity versus shear rate curves of an A-Matrix suspension containing 42 vol.% in presence of a) 0.2 wt.% (based on solids amount in suspension) of Dolapix PC33 and Dolapix A88, and b) Dolapix A88 + CMC [13]

Solvent debinding was performed at 44°C for up to 20 hours, and the parts were then debound and sintered in vacuum (1440°C, 1465°C) or pressure sintered at 1435°C using 120 MPa (17 bar) Ar overpressure (Fig. 13). Shrinkage was ~23% in the xy plane and ~25% in the z axis. Due to C levels being off-target after sintering, there was some eta phase present and thus optimal sintered properties were not obtained, but the parts were fully dense. It was stated that with process refinement, C levels would be optimised.

Green parts formed with lower solids loading slurries

A presentation by M S Faria and colleagues, University of Aveiro, and co-authors from Palbit S.A., Portugal, described work forming shapes from a Si_3N_4, Al_2O_3, and Y_2O_3 powder-loaded (38 vol.%) aqueous solution of four organic additives to form an 'ink' [13]. Also referred to as Robocasting, this process is related to the standard Material Extrusion process, but with lower viscosity, and typically lower solids loading, slurries being processed to form a green part.

Viscosity testing was performed to aid material optimisation, with the authors stating that the 'ink' was extruded at room temperature through a 410 µm diameter nozzle at 10 mm/sec to form rectangular-shaped green parts (Fig. 14). After drying, debinding, and sintering in a N_2 atmosphere, shrinkage, density, and hardness were measured: linear shrinkage at 26.8% was higher than pressed and sintered comparisons, while density and hardness were at the low end of the range of controls. The basic microstructure was similar to controls, but there were areas of porosity thought to originate at the boundaries of extrudate 'lines' and from the debinding process (Fig. 15). Nevertheless, with further optimisation, the process looks promising for future application.

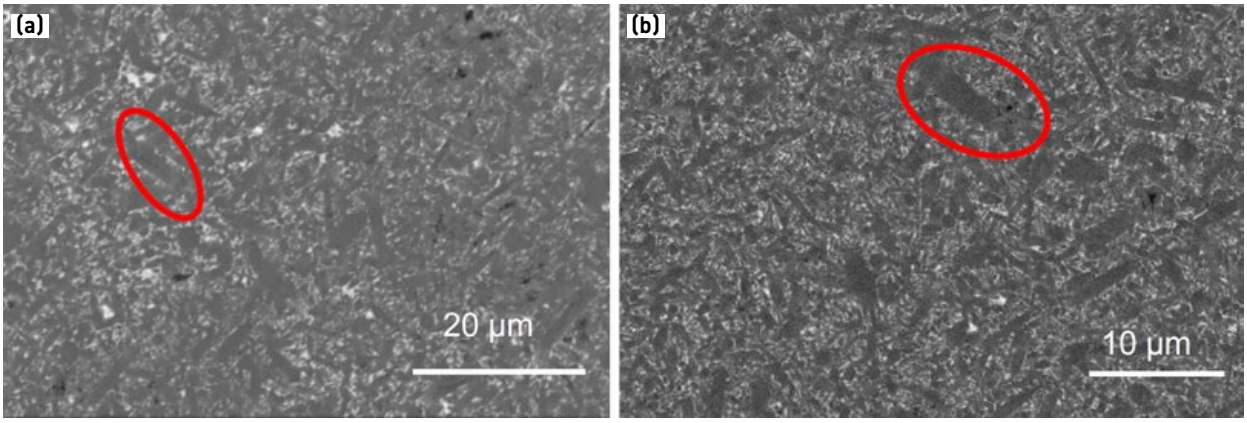

Fig. 15 Micrographs of a) sample obtained by robocasting, b) sample processed by uniaxial pressing [13]

Microgravity sintering

One of the expectations of AM processes is that they would be used in space, in either zero gravity (in orbit) or low gravity (for example, the Earth's moon or Mars) to manufacture components or protective structures for long-term space missions. Randall German and co-authors, San Diego State University, USA, gave a progress report on experiments sintering 85W 5Ni 5 Cu 5 Mn (by wt.%) alloy under terrestrial conditions and in the International Space Station in earth orbit [14]. The study uses a model liquid-phase sintering system (tungsten heavy alloy) to understand in what way, and by how much, dimensional and structural integrity differ by sintering in zero or low gravity versus on Earth. Earlier work showed large differences in both, attributed to the absence or reduction of both pore buoyancy and gravity-induced compression in zero or reduced gravity.

Process comparisons

While not strictly a part of 20th Plansee Seminar, the Hard Materials Research Group of the European Powder Metallurgy Association (EPMA) held a half day meeting during the Seminar, which included a presentation by Johannes Pötschke, Fraunhofer IKTS Dresden, Germany, summarising the EPMA club project AddiHM, focused on the 'Additive Manufacturing of Hardmetals by Non-Laser Processes'. The project is dedicated to the memory of the late Dr Leo Prakash.

Partners in the work, to be managed by EPMA, are Fraunhofer IKTS Dresden, Tecnalia (Spain), KU Leuven (Belgium), Polytechnic University of Catalonia (Spain), and, so far, eight industrial partners – more may join. A twelve-month timeframe is anticipated after the work is officially kicked off. The project will compare the same WC-12 wt.% Co powder composition in three different AM processes: Binder Jetting, filament-based Material Extrusion, and Material Jetting, as well as conventional uniaxial pressing for control samples, and will thus involve feedstock preparation, green part formation, sintering, and the evaluation of shrinkage, microstructure, magnetic properties, mechanical testing, and fractography. The study will allow objective and quantitative comparisons of the processes with each other as well as conventional processing.

In another process comparison presentation, Tim Gestrich and colleagues, Fraunhofer IKTS, Dresden, discussed the pros and cons of the Binder Jetting and filament-based Material Extrusion processes for the AM of cemented carbides and presented the results of thermal analysis using thermogravimetric analysis, dilatometry, differential scanning calorimetry, mass spectroscopy, and Fourier transform infrared spectroscopy [15]. These techniques give deep knowledge of outgassing, organics removal, surface oxides reduction, and the sintering behaviour of materials, and can be used to optimise sintering cycles.

Five cemented carbide compositions were studied, all ultrafine WC 9 or 10 wt.% Co with Cr_3C_2+VC additions. The thermal analysis showed differences in behaviour according to the different additives used for the green forming processes, and for the binder jetted material, an absence of the normal surface oxide reduction step, which can be explained by the pre-sintering of granules prior to Binder Jetting.

Takeaways

Considering the several presentations discussed above, together with past published data, and including AM processes which were not specifically addressed at the seminar, a number of summary statements seem reasonable:

A diversity of processes

There are numerous distinct processes in contention for the AM of cemented carbides – those discussed in this review, as well as the PBF-EB process used by, for example, Sweden's VBN Components. A further process is Headmade Materials' Cold Metal Fusion [16], which has already been applied to metallic

"...while the AM of cemented carbides is clearly a growth area, one should not underestimate the practical difficulty of replacing existing processes with decades of refinement behind them, as well as economies of scale."

tungsten. Here, heavily powder-loaded polymer granules are fused in a PBF-LB machine designed for the processing of polymers to form green parts, and said parts are subsequently debound and sintered.

Binder Jetting leads the pack
It appears that Binder Jetting is, currently, the furthest along in terms of implementation, followed by Material Extrusion. However, it is still a horse race between these and other processes. Very smart people and organisations are investigating all of them.

Each process has advantages and disadvantages
The Binder Jetting process has advantages in terms of build rate, easy debinding, and (based on appearance in images) reasonable surface finish quality. The filament-based MEX process has the advantages of not needing pre-sintering of the WC-Co feedstock, of forming parts with closed internal cavities (since no depowdering is required) and, in some cases, potentially higher green densities and lower shrinkage rates. It is too early to say with confidence what the pros and cons of other processes are.

An ever-broadening range of cemented carbide grades
The grade (primarily Co level and WC grain size) range addressable with Binder Jetting is expanding rapidly, through greater process knowledge and refinement. Only a year ago, 17 wt.% Co grades were the only ones openly available, but that seems to have broadened to 12% Co now, with 10% Co on the brink of commercialisation, and at a wide range of grain sizes. Given that the two largest families of cemented carbides are at the 6 and 10 wt.% Co levels respectively, this is very important.

A technology with huge market potential
For this author, the Kennametal presentation was especially significant because the 10% Co submicron grade successfully produced by Binder Jetting into high-quality material is of a type almost ubiquitous for solid round carbide tooling, which is a very large market, and an AM route has some potential benefits over existing processes.

Concluding remarks

While the AM of cemented carbides is clearly a growth area, one should not underestimate the practical difficulty of replacing existing processes with decades of refinement behind them, as well as economies of scale. In this author's view, AM processes will supplement and complement existing processes far more than replace them. The next (21st) Plansee Seminar will be held in May/June 2025. It will be fascinating to see how much additional progress the Additive Manufacturing of refractory metals and hard materials will have made by then.

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Fig. 16 The opening ceremony of the Plansee Seminar 2022 (Courtesy Plansee Group)

Fig. 17 Delegates outside the Plansee Seminar (Courtesy Plansee Group)

Fig. 18 Location of the Plansee Seminar 2022 (Courtesy Plansee Group)

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Ceramitec 2022: Opportunities abound for producers of technical ceramics by CIM and AM

After a four-year interruption due to COVID-19, Ceramitec, the leading trade fair for the ceramics industry, reopened its doors at Messe München, Germany, from June 21–24, 2022. Whilst noticeably smaller than in previous years, and with significant gaps in the floor plan from the industrial ceramics sector, the event appears to have been positive for the technical ceramics community. Dr Georg Schlieper visited the exhibition for *PIM International* and reports on activities of interest to users of Ceramic Injection Moulding and ceramic Additive Manufacturing technologies.

Ceramitec 2022 was held under difficult circumstances. The COVID pandemic was still in the forefront of many people's minds and some countries, including, crucially, China, still imposed severe travel restrictions, limiting participation from Asia. Furthermore, geopolitical uncertainties inevitably impacted on the industry's willingness to invest.

Despite these circumstances, Ceramitec's organisers were confident about the success of the trade show, driven in large part by the knowledge that there was a strong desire for face to face contact between suppliers and customers. In the end, and whilst regarded as a success by many of those who participated, with 356 exhibitors compared to 633 in 2018, and a reported 'around 10,000 visitors' compared to more than 15,000 in 2018, the figures suggest a slower than hoped-for return to normality.

It should be recognised, however, that many of the absences from the floorplan were from the 'non-technical ceramics' halls, where suppliers of major capital equipment were, it was suggested by some observers, at once dealing with the challenging geopolitical environment and full order books as life returned after COVID, limiting the benefits of seeking new business at a trade show.

Within the realm of technical ceramics, however, rich opportunities exist for CIM producers to diversify into ceramic AM and, indeed, based on informal conversations, it is now hard to find a CIM producer who isn't already investing in ceramic AM to some extent.

In this report, we have selected a sampling of exhibitors whose CIM or ceramic AM offerings highlight the diversity of activity in this field.

Fig. 1 Visitors arriving at Ceramitec 2022 (Courtesy Messe München)

Fig. 2 CIM feedstocks, binders and sample parts on display at Inmatec's stand at Ceramitec 2022

Fig. 3 Krahn Ceramics is actively involved in the development and production of materials for ceramic Additive Manufacturing (Courtesy Krahn Ceramics)

Materials for CIM and ceramic AM

Inmatec Technologies GmbH

Inmatec Technologies GmbH, Rheinbach, Germany, has been producing feedstocks for the CIM industry since 1998. Dr Karin Hajek, Inmatec's Sales Director, explained the evolution of ceramic feedstocks at the company, "In the beginning, our feedstocks were based on a binder system that had to be debound in two steps: first solvent debinding in water, followed by a thermal process. Over the years, as CIM technology matured, the demand for more sophisticated feedstocks arose. Inmatec developed further binder systems based on various thermoplastic polymers and, today, a wide range of ceramic feedstocks for various debinding processes is available."

Inmatec has grown continuously in recent years, driven by the expanding market for CIM products. "Today, we employ about sixty people," stated Hajek. "Ceramic feedstocks are produced on eight production units. Particular attention is paid to the purity of the feedstocks as well as sophisticated quality control procedures adapted to different material compositions."

Hajek stated that, through active participation in the committees of the German Ceramic Society, the European Ceramic Society and, last but not least, the German-language Expert Group on Ceramic Injection Moulding (Expertenkreis Keramikspritzguss), it has been possible to significantly increase awareness of CIM technology and to extend its technical development into new areas.

Members of the Expert Group on Ceramic Injection Moulding organised a panel discussion at Ceramitec on the possibilities for CIM technology. Case studies from various application areas were presented under the moderation of Inmatec's Managing Director, Dr Moritz von Witzleben.

Krahn Ceramics

As part of the global, family-owned Otto Krahn Group, Krahn Ceramics specialises in feedstocks for MIM, CIM and sinter-based Additive Manufacturing. Based on a range of proprietary binder systems for debinding in water or organic solvents, as well as for catalytic or thermal debinding, Krahn Ceramics develops and produces customer-specific kcmold® feedstocks. Additionally, Krahn Ceramics offers its organic binders under the brand name Embemould®, as well as several special organic additives in its kcmix® product range, for the production of CIM/MIM feedstocks. In the company's technical centre, new products are developed and prepared for release.

Besides the feedstock granules for MIM and CIM technology, Krahn Ceramics also produces filaments for Material Extrusion (MEX) Additive Manufacturing. The company has established in-house

Fig. 4 View of the one area of the technical ceramics hall at Ceramitec 2022

capacities for manufacturing filaments, supported by what it states is a comprehensive customer service offering.

EnCeram

EnCeram, a subsidiary and in-house start-up within Chemische Fabrik Budenheim KG, Budenheim am Rhein, Germany, has historic connections with ceramic feedstock supply. According to Dr René Engelke, Managing Director of EnCeram, the market launch of the first products based on a water-soluble binder for the production of components made of alumina and zirconia is planned for the end of 2022.

Innovative process developments for ceramics

Lithoz GmbH

Austria's Lithoz GmbH is widely known for its Vat Photopolymerisation (VPP)-based Additive Manufacturing machines for ceramics and is regarded as the market leader in this field in both commercial and technological terms.

Martin Mann, Head of Sales at Lithoz, showed *PIM International* some application examples of this technology, which demonstrate the versatility of the process, including various Laval nozzles for burners of all kinds. Functional materials such as piezoelectric and dielectric materials can also be additively manufactured using the process, while special bioceramics are available for medical and dental applications. Geometrically complex lost cores for investment casting are made of special silica-based ceramics. Such cores are used in the production of turbine blades manufactured from heat-resistant nickel superalloys and applied in gas turbines and aircraft engines.

The VPP process that Lithoz uses, which the company refers to as Lithography-based Ceramic

"Geometrically complex lost cores for investment casting are made of special silica-based ceramics. Such cores are used in the production of turbine blades manufactured from heat-resistant nickel superalloys and applied in gas turbines and aircraft engines."

Fig. 5 Alumina parts produced on Lithoz's VPP-based ceramic AM machines: A 12 cm tall combustion chamber and a scaled aerospike engine demonstrator

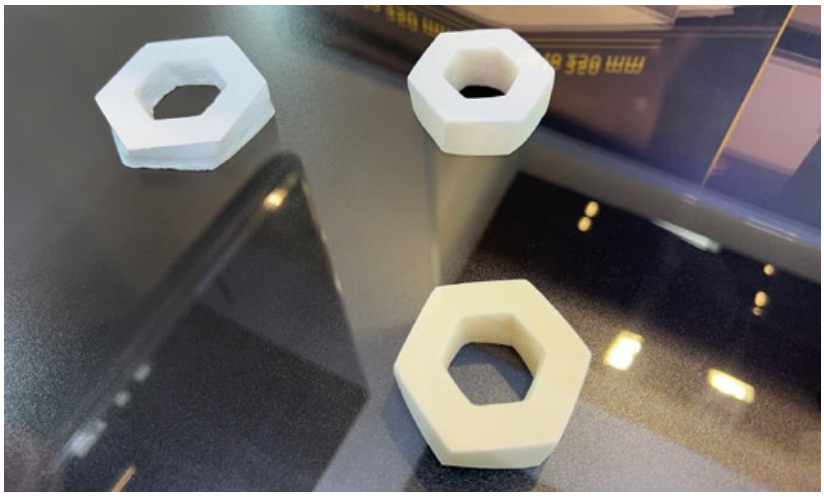

Fig. 6 Sample geometries produced using Lithoz's new Laser-induced Slipcasting (LIS) technology, designed for large-scale parts

Manufacturing (LCM), requires debinding and sintering after the moulding step. During sintering, a shrinkage of about 35–40% takes place. The surface quality and precision achieved with the process is comparable to that of CIM, but with greater shaping complexity.

In addition to the VPP-based process, Lithoz presented a new technology for larger, fully dense ceramic parts that it calls Laser-induced Slipcasting (LIS). Here, a water-based slurry is selectively dried with a laser, thus building up the component in a layer by layer fashion. This process does not allow the same precision as VPP, but is suitable for the production of large, thick-walled components. If necessary, parts can be machined in the green state and then sintered, with the debinding step omitted as the water evaporates when drying.

AON

Another VPP-based Additive Manufacturing machine for ceramic materials was presented by the Korean company AON. Starting from the manufacture of dental products, the company's technology was developed to such an extent that, today, small precision parts can be produced from alumina, zirconia and silicon nitride. AON's Additive Manufacturing machines are available in a variety of sizes, with the maximum build space being 107 x 60 x 150 mm.

Pollen AM

Pollen AM is a young French company led by Didier Fonta. The starting point of his development work was the recognition that many AM processes offer only a limited selection of materials; Pollen AM set itself the goal of developing a machine for Additive Manufacturing, which is suitable for polymers, ceramic and metallic materials.

The resultant Material Extrusion (MEX) machine can be used to process the same granulated feedstock pellets used in plastic injection moulding as well as MIM and CIM. Whilst this variant of MEX technology

Fig. 7 One of Pollen AM's Material Extrusion (MEX) machines (Courtesy Pollen AM)

Fig. 8 A Binder Jetting (BJT) machine manufactured by Concr3de (Courtesy Concr3de)

is also being developed by others in the market, one example being Germany's AIM3D, in the case of Pollen AM, it is referred to as Pellet Additive Manufacturing (PAM). The AM machine presented (Fig. 7) had a build space of 30 cm in diameter and 30 cm in height. The build plate and the installation space are heatable. The most important components are the four build heads, which can be filled with different materials, if required.

Each build head has a reservoir into which pellets are filled. In a micro-extruder that works in the same way as the extruders of an injection moulding machine, the material is plasticised and compacted so it can be pushed through a fine nozzle. In this way, the green part is built up in the same way as filament-based MEX, also known as Fused Filament Fabrication (FFF).

As attractive as the process may seem at first glance – especially for manufacturers of MIM and CIM components, who are known to have all systems for debinding and sintering – one should bear in mind that there are a large number of parameters that must be optimised for each material in order to end up with a high-quality product.

The ceramic parts manufactured so far by Pollen AM are made of aluminium oxide, zirconium oxide, silicon nitride, and silicon carbide.

3D Minerals

3D Minerals is a French start-up that develops MEX-based ceramic Additive Manufacturing machines. The additive process used is referred to by the company as Slurry Deposition Modelling (SDM) or Paste Deposition Modelling (PDM), a name that echoes the historic term Fused Deposition Modelling (FDM), now referred to as Material Extrusion under ISO/ASTM 52900:2021 Additive Manufacturing — General principles — Fundamentals and vocabulary.

In the process, a suspension of ceramic powder and a liquid is pressed through a fine nozzle and deposited on the build, thus building the green part up layer by layer. The green part is then further processed by drying and sintering or firing to the finished product.

Three basic types of AM machine are offered:

- A Cartesian AM machine, which uses the x, y and z axes as parameters during manufacturing
- An AM machine with a rotating mounting plate, particularly suitable for manufacturing rotationally symmetrical components
- An AM machine with a robotic arm, which offers increased flexibility in terms of product geometry

The AM machines offered by 3D Minerals are suitable for the production of very large parts made from technical ceramics, porcelain or earthenware.

Concr3de

Concr3de, Rotterdam, is a Dutch company which manufactures Binder Jetting (BJT) machines (Fig. 8). With three different machine types, the company covers an extremely wide range of materials, from types of rock such as marble, granite, limestone and concrete to various ceramic materials, as well as selected metals. The company

Fig. 9 Bosch Advanced Ceramics' stand focused on the potential for ceramic Additive Manufacturing for industrial production

Fig. 10 Steinbach AG promoted its expertise in the ceramic Additive Manufacturing of, in particular, components for industrial and medical applications

> *"Bosch Advanced Ceramics presented itself as a manufacturer and engineering partner for high-quality precision parts made of oxide ceramics via CIM and AM. The company was founded as a corporate startup within the Bosch Group with the task of using ceramic AM for industrial production."*

supports its customers in the development of additively manufactured products.

One target is large building elements made of concrete or rock-like materials with dimensions of up to 6 metres. Eric Geboers, CEO of Concr3de, told *PIM International* that Binder Jetting is able to additively manufacture such large parts in a relatively short time.

Users of AM technology

Bosch Advanced Ceramics

Bosch Advanced Ceramics presented itself as a manufacturer and engineering partner for high-quality precision parts made of oxide ceramics via CIM and AM. The company was founded as a corporate startup within the Bosch Group with the task of using ceramic Additive Manufacturing for industrial production.

From the very beginning, the VPP process was applied (Fig. 6). Working closely with manufacturers of ceramic AM machines, the technology and processes have been adapted to the requirements of industrial production. As a result, Bosch Advanced Ceramics has been able to quickly gain a leading position in the field, building on the Bosch Group's years of experience in manufacturing CIM parts.

Steinbach AG

Germany's Steinbach AG offered its expertise in the Additive Manufacturing of engineering ceramics for industrial and medical applications, a field in which the company has been active since 2016. Steinbach uses Lithoz AM machines to manufacture green parts with layers of 25-100 µm, which, upon completion, are cleaned, debound and sintered.

Steinbach uses this process to produce components made of alumina and zirconia. The maximum dimensions of the products are about 80 x 50 x 150 mm (x/y/z). The shrinkage during sintering is stated to be about 30%. The achievable

Fig. 11 Producers of CIM and ceramic AM parts were highly visible at Ceramitec 2022, including, from top left to bottom right: Oechsler AG, Maxon Group, Small Precision Tools (SPT), Indo-MIM, and Kläger Spritzguss GmbH & Co KG

dimensional accuracy is ±1% of the nominal dimension, with a maximum of ±0.1 mm.

Schunk Technical Ceramics
Schunk Technical Ceramics impressed with very large additively manufactured exhibits made of silicon-infiltrated reaction-bonded silicon carbide RBSiC. This extremely hard, temperature- and corrosion-resistant material is suitable for highly stressed applications. AM technology makes it possible to produce highly complex components in one piece.

Conclusion

Visitors at Ceramitec 2022 were able to see that the development of AM processes is still in full swing. The most well-known technologies have been further developed to series maturity. This is, in turn, opening up the use of technical ceramics by new customers as the restrictions imposed by tooling costs, necessitating larger volumes, are being lifted. It will be exciting to observe the technology's further development.

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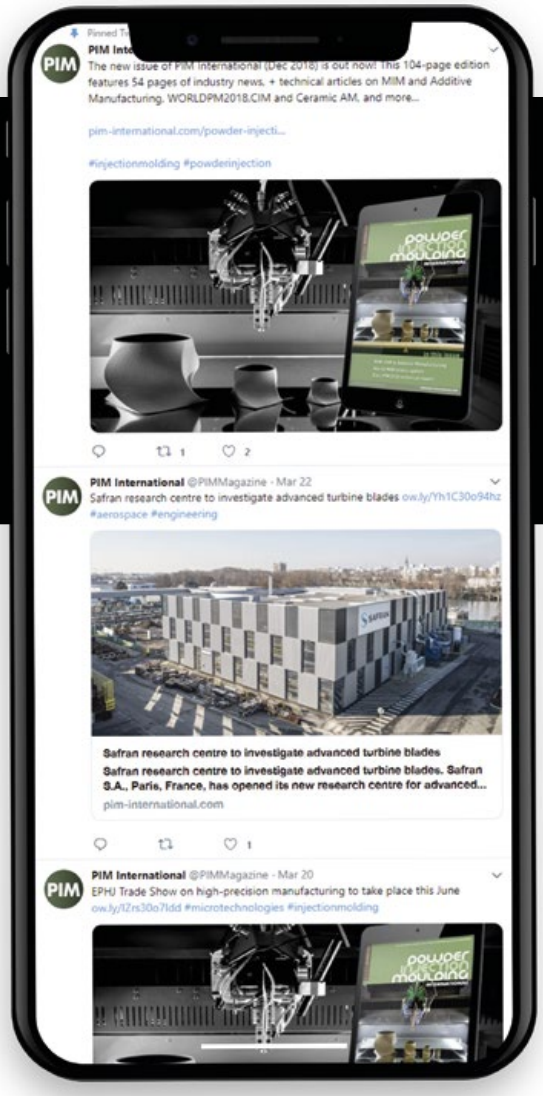

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www.worldpm2022.com

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Dresden, Germany
www.am-ceramics.dkg.de

EuroBLECH 2022
October 25–28, 2022
Hannover, Germany
www.euroblech.com

Formnext
November 15–18, 2022
Frankfurt, Germany
www.formnext.com

Hagen Symposium 2022
November 24–25, 2022
Hagen, Germany
www.pulvermetallurgie.com/symposium-termine/symposium-aktuell

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February 27–March 1, 2023
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www.mim2023.org

AMUG
March 19–23, 2023
Chicago, IL, USA
www.amug.com

Hannover Messe 2023
April 17–21, 2023
Hannover, Germany
www.hannovermesse.de

Ceramics Expo 2023
May 1–3, 2023
Novi, MI, USA
www.ceramicsexpousa.com

RAPID + TCT
May 2–4, 2023
Detroit, MI, USA
www.rapid3devent.com

PowderMet2023 / AMPM2023
June 18–21, 2023
Las Vegas, NV, USA
www.powdermet2023.org / www.ampm2023.org

EMO Hannover 2023
September 18–23, 2023
Hannover, Germany
www.deutschemesse.co.uk/emo

Euro PM2023
October 1–4, 2023
Lisbon, Portugal
www.europm2023.com

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