Frank Petzoldt on MIM’s evolution
Saturation in Binder Jetting
Industry insight from MIM2022
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The mystery of the missing MIM research

The PM World Congress series has always been a rich source of information on the direction of MIM research, with papers from around the world shining a light on what we can expect to see in the next generation of MIM components.

This year sees the delayed return of the PM World Congress series to Europe, but with the recent publication of World PM2022’s technical programme it is clear that the number of MIM sessions is much reduced.

Can this be attributed to a new post-COVID world order, where some remaining travel restrictions or a sense of caution have limited participation? Perhaps it is simply that research in MIM has tailed off, in part as a result of the state of maturity of the process? Or, more likely, that the efforts of those in academia, as well as in MIM houses themselves, are focused on exploring the opportunities presented by sinter-based AM technologies that may expand business opportunities.

It is certainly the case that many familiar faces from PM and MIM part producers are now being seen in greater numbers than ever at exhibitions focused on Additive Manufacturing. That those from our industry now have a much more diverse range of events to choose from is undeniable. The competition for people’s precious time is becoming tougher than ever.

As someone who has attended many PM World Congresses since the distant days of the PM’94 World Congress, I hope that this year’s event will live in the memory as ‘one of the greats,’ but it will take a stronger effort than ever for it to do so.

Nick Williams,
Managing Director & Editor
Production 3D printing starts here
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Frank Petzoldt on the past, present and future of Metal Injection Moulding technology

There can be few people in Europe’s MIM industry, if not further afield, who are unaware of Prof Dr Frank Petzoldt’s contribution to the development and promotion of the technology over more than three decades.

Following his recent retirement from the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Bremen, Germany, Dr Petzoldt spoke with Dr Georg Schlieper about the past, present and future of MIM technology and shares his insight into the industry in both Europe and worldwide. >>>

Saturation in metal Binder Jetting: Simple in principle, complicated in practice?

As metal Binder Jetting (BJT) transitions from a technology for the future to a technology for now – and one that is increasingly being installed at Metal Injection Moulding producers around the world – one of the basics of the process that we can no longer avoid getting to grips with is saturation.

In this article, longtime metal Binder Jetting expert Dan Brunermer, from technology consultancy B-jetting LLC, explains saturation and how to measure it, considers voxels and DPI, and finally presents control options and how choices in controls affect saturation. >>>

Industry insight from the 2022 International Conference on Injection Molding of Metals, Ceramics and Carbides

In the programme of the 2022 International Conference on Injection Molding of Metals, Ceramics and Carbides (MIM2022), organised by the Metal Powder Industries Federation (MPIF) and held in West Palm Beach, Florida, USA, a number of presentations reported on innovations in both Metal Injection Moulding and the closely related sinter-based Additive Manufacturing process.

In this report, Dr Satya Banerjee, Bishoi Consulting Co. LLC, reviews his highlights from the conference programme. >>>
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Ceramics in new dimensions: Additive Manufacturing at CeramTec

No matter which market report you choose to believe, all recent analysis of the ceramic AM market points to major growth. But this is still an emerging technology, and in terms of its commercial development, ceramic AM is said to be five years behind metal AM. Now, as global manufacturers of high-performance ceramics enter the market, an even faster acceleration in technology adoption is promised. Here, Claus Falkner, of CeramTec, a producer of technical ceramics by processes that include Ceramic Injection Moulding, explores the benefits of ceramic Binder Jetting and considers the process as a compelling solution for complex parts. 

Understanding the carbon footprint of injection moulding machines

Arburg GmbH + Co KG, Lossburg, Germany, has been working intensively on sustainability and resource efficiency for a very long time. As the supplier of the widely used Allrounder line of injection moulding machines, the company is increasingly active in evaluating climate protection activities along the entire value chain for its customers. On the basis of ISO TS 14067:2018 – a standard that defines a product’s greenhouse gas emissions or Product Carbon Footprint (PCF) – Bertram Stern, Sustainability Manager at Arburg, reports on how the PCF and specific energy requirements of Arburg injection moulding machines can be calculated.

The maths in the magic: Calculating the sintering shrinkage of MIM parts

Newcomers to Metal Injection Moulding never cease to be amazed when they see that green parts uniformly shrink during debinding and sintering into a finished part.

This calculated shrinkage, which is what enables products to conform to an engineer’s blueprints, can appear pretty magical. It is, of course, simply a matter of mathematical calculation.

In this article, Dr Chou Yau Hung (Dr Q) and James Chao, from You need Technology Office, Taiwan, encourage you not be scared off by the mathematics and discover the calculations at the heart of MIM.

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Discover the leading suppliers of materials and equipment for MIM, CIM and sinter-based AM, as well as part manufacturing partners and more.

106 Events guide

View a list of upcoming events for the MIM, CIM & sinter-based AM industries.
# MIM Powder Manufacturer

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Kennametal becomes GE Additive Beta Partner to advance tungsten carbide Binder Jetting capabilities

GE Additive has announced that Kennametal Inc., Pittsburgh, Pennsylvania, USA, is the latest member of its Beta Partner Programme. As part of the GE Additive Programme, Kennametal will further advance its Binder Jetting (BJT) production capabilities in tungsten carbide, as it continues to scale its end-to-end metal Additive Manufacturing operations.

Kennametal offers a complete Additive Manufacturing solution, from high-performance metal powders through to the production of additively manufactured components and tooling. Its metal AM parts have already gained wide customer adoption across a variety of industries, such as oil & gas, energy, industrial processing and transportation. The company will work with GE Additive to identify, design and scale specific applications for serial production on GE’s Binder Jetting system, leveraging Kennametal’s proprietary cemented tungsten carbide materials.

“Customers are increasingly seeking our 3D printed tungsten carbide and Stellite [cobalt chrome alloy] solutions to help them maximise their productivity in challenging applications when wear and corrosion resistance are critical,” stated Jay Verellen, General Manager, Kennametal Additive Manufacturing.

“Our work with GE Additive on binder jet solutions will enable further scaling of our operations to meet strong customer demand — and extend our leadership in proprietary material solutions for additive.”

GE Additive is continuing to develop its Binder Jetting solution to make Additive Manufacturing a reality for serial production, targeting millions of parts per year and beyond. Key to that development is ongoing, hands-on input from members of GE Additive’s Binder Jet Beta Partner Programme.

“By hands-on, we don’t mean tinkering or experimenting. We work closely with our beta customers as they develop their own, real-world business cases, applications and parts. To them, it is important that our solution is not only mature and scalable but is capable, complete and aligns to their product innovation strategies and meets production volume needs,” added Brian Birkmeyer, product line leader for Binder Jet at GE Additive.

“We are honoured that Kennametal, an industry leader in 3D printed tungsten carbide, is working closely with us on the development of our binder jet platform. Ensuring we align with Kennametal’s production expectations and requirements is a top priority. Their longstanding expertise in materials science mirrors our own, and our team is excited to work together to deliver new and innovative solutions,” concluded Birkmeyer.

www.kennametal.com
www.ge.com/additive

Series 3 of GE Additive’s Binder Jet Line Additive Manufacturing machine (Courtesy GE Additive)
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SSI Sintered Specialties changes name to DSB Technologies

SSI Sintered Specialties, LLC, a manufacturer of sintered metal components headquartered in Janesville, Wisconsin, USA, has changed its name to DSB Technologies. Following an extensive rebrand, the name change is intended to build on the company’s recent technology expansion, which has seen investments in Powder Metallurgy, Metal Injection Moulding and metal Binder Jetting (BJT) Additive Manufacturing technologies over the last year.

“This organisation has an impressive history and an even brighter future ahead,” stated Paul Hauck, COO of DSB Technologies. “From the earliest days, we have operated with a drive for innovation. As our company and customer base continues to evolve, this rebranding embodies our commitment to the growth needed to be a prominent manufacturing partner.”

For over forty years, DSB Technologies has collaborated with its customers as a metallurgical solutions partner for high-performance Powder Metallurgy components. Under the name SSI Sintered Specialties, it operated as the sintered components division of SSI Sintered Specialties, LLC, a successful precision engineering organisation led by the company’s current ownership. In 2019, SSI Sintered Specialties was separated from the organisation and took the opportunity to leverage its existing capabilities and expand the business into new technologies, applications, and markets.

“SSI was historically known as a conventional press and sinter business, but there is so much more at the core of our company,” Hauck added. “Our new company name allows us to adopt new technology more freely and bring to light the industry-leading talent and vast expertise we offer to our customers.”

With a committed focus on growth, DSB Technologies is reportedly combining its present Powder Metallurgy and manufacturing knowledge with new technology and talent investments to continue designing and engineering complex, functional, PM components. The company houses what is believed to be North America’s largest capacity of high temperature sintering furnaces in its 23,226 m² facility in Janesville, along with a fleet of over thirty-five presses, a vast range of secondary operations, a hands-free moulding cell and an in-house automation team.

www.dsbtech.com

Ultra Fine Specialty Products adds pilot atomiser for powder development

Ultra Fine Specialty Products, LLC, an affiliate of Novamet Specialty Products Corporation, reports that its manufacturing site in Woonsocket, Rhode Island, USA, has installed capabilities to produce pilot quantities of gas atomised powders. This is expected to enable the development of custom alloys based on iron, cobalt, nickel, and copper for Powder Bed Fusion (PBF) and Binder Jetting (BJT) Additive Manufacturing, as well as Metal Injection Moulding.

Ultra Fine Specialty Products’ pilot and production atomisers utilise a unique gas atomisation process to produce high-purity spherical metal powders with tightly sized particle distributions (d90 <30 µm) to meet customers’ stringent specifications for MIM and metal Additive Manufacturing, particularly applicable to BJT.

The newly commissioned pilot atomiser enables orders of as little as 50 kg, reducing the amount of material that customers must purchase for development projects. Upon successful evaluation, quantities can be readily scaled to high volumes on existing production equipment. The pilot equipment will enable the development of technology to further optimise particle size distributions, improve sphericity, and reduce satellites to facilitate the growth of these processes.

Ultra Fine Specialty Products was purchased on June 30, 2020, from Carpenter Technology by a group of investors affiliated with Novamet. Novamet Specialty Products Corporation was formed in 1976 to apply technology to the development of nickel-base powders with unique morphologies, shapes, and sizes. The company currently processes and distributes various metal powders and coated products for the MIM, aerospace, automotive, coatings and electronic materials markets.

www.ultrafinepowder.com
www.novametcorp.com
Industry News

**Digital Metal launches DMP/PRO series for industrial Binder Jetting**

Digital Metal, part of Sweden’s Höganäs Group, has launched its DMP/PRO series Binder Jetting (BJT) Additive Manufacturing machine. Developed as a modular component of a complete binder jet solution, the PRO series is designed to offer maximum reliability, accuracy and repeatability in high-volume industrial manufacturing. The DMP/PRO’s printhead incorporates 70,400 nozzles, enabling the machine to produce up to 1,000 cm³ of parts per hour at 1600 dpi. Typical production values, claims Digital Metal, will see customers produce around 500 cm³ of parts per hour throughout the day.

The new DMP/PRO is designed to be part of a complete modular Binder Jetting solution, enabling high volume Additive Manufacturing (Courtesy Digital Metal)

**Triditive and Foxconn partner to develop Binder Jetting machine**

Foxconn, the trading name of Hon Hai Technology Group, a leading electronics manufacturing company headquartered in New Taipei City, Taiwan, and Triditive, a producer of automated Additive Manufacturing technology based in Asturias, Spain, have partnered to develop a new Binder Jetting (BJT) AM machine.

Both companies are currently developing their first prototype Binder Jetting machine, along with the materials required for subsequent commercialisation.

For the development of the binders, Triditive has collaborated with Tecnalia, the research and technological development centre of the Basque Country (País Vasco), Spain. It has also worked with the Fraunhofer Technology Center High Performance Materials (Fraunhofer THM) for the selection of metal powders.

The key advantages of the innovative technology that Foxconn and Triditive are developing is reported to be the scalability of production and a reduction of costs in the manufacture of complex metal parts for end-use applications.

www.foxconn.com
www.triditive.com

www.digitalmetal.tech
World leading MIM powder company reinvents AM material.
Ecrimesa expansion brings facilities to total 20,000 m²

Ecrimesa Group, based in Santander, Spain, a manufacturer of steel and aluminium parts by Metal Injection Moulding and investment casting, has extended its facilities to a total area of around 20,000 m². The facility includes a technical office, a moulding workshop, machining plant, areas for investment casting, Metal Injection Moulding, Additive Manufacturing, a metallurgical laboratory and metrology department.

Earlier this year, Ecrimesa received delivery of two Arburg Allrounder 370 A injection moulding machines and was expecting a Cremer MIM Master continuous debinding and sintering furnace to bolster its MIM operations.

Over the past decade, Ecrimesa has increased its production capacity by more than 25%, both in terms of physical and human resources, with a turnover increase of over 40%.

Ecrimesa added that it plans for the Santander plant to exceed €45 million turnover in 2022, compared to €42 million in the previous year.

www.ecrimesagroup.com

X-ray and CT systems supplier Yxlon to become Comet Yxlon

Yxlon International, Hamburg, Germany, has announced plans to change its name to Comet Yxlon, effective September 8, 2022. The new brand is said to underscore the company’s long-standing affiliation with plasma and X-ray solutions provider Comet, based in Flamatt, Switzerland.

Yxlon develops, manufactures and markets high-end X-ray and CT system solutions for industrial environments, from R&D labs to production environments, with integrated services based on artificial intelligence and data analytics. It has been part of parent company Comet Holding AG, which unites a global group of technology businesses under its umbrella, since 2007.

“The Comet Yxlon brand represents decades of X-ray expertise and a passion for making new things possible – in line with the motto ‘Led by experience. Driven by curiosity,’ ” stated Kevin Crofton, CEO of Comet Group and interim president of Yxlon. “The rebranding strengthens our presence and reaffirms our importance within Comet Group.”

www.comet-group.com

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Kymera International acquires titanium powder maker AmeriTi Manufacturing

Kymera International, a speciality materials company headquartered in Raleigh, North Carolina, USA, has acquired AmeriTi Manufacturing Company, Detroit, Michigan, USA. AmeriTi is a manufacturer of value-added ferrotitanium, titanium sponge, titanium powders and specialty forms. The terms of the transaction were not disclosed; however, AmeriTi’s parts business, known now as TriTech Titanium Parts, was not included in the transaction.

“AmeriTi is a growing company led by a talented, dedicated employee base that culturally aligns with our mission and objectives to be the leading manufacturer of specialty materials that shape the future,” stated Barton White, CEO of Kymera. “We believe this is a synergistic acquisition that will give our combined company strong technical and commercial resources to help fuel our growth in the aerospace, medical, defense, and industrial markets.”

AmeriTi produces titanium powder using the hydride-dehydride (HDH) process and is able to manufacture both commercially pure and alloyed titanium powder in a wide range of particle sizes. The company is said to have the unique ability to supply enriched alloy powder. This includes enriching powder with alloying elements that are lost during post-processing steps. An example of this is an enriched aluminium version of Ti 6-4 to compensate for aluminium loss during Laser Beam Powder Bed Fusion (PBF-LB) Additive Manufacturing.

Bob Swenson, the owner of AmeriTi for the past twenty-five years, added, “The sale of AmeriTi to Kymera is an exciting next step for the business. Kymera and AmeriTi together will continue to build the product lines and grow into new areas. The combined business will be able to build on its titanium experience and knowledge, and maintain its strong customer focus and service.”

Kymera International is owned by the private investment firm Palladium Equity Partners. “We are thrilled to help support the acquisition of AmeriTi, Kymera’s fifth to date under Palladium’s ownership, and second completed over the last three months,” stated Adam Shebitz, a partner at Palladium. “The addition of AmeriTi will help to realise Kymera’s five-year business plan to diversify into new, margin accretive, and growing end markets.”

www.kymerainternational.com
www.ameriti.com

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Spyros Panopoulos Automotive (SPA), Acharnes, Greece, has developed what is reported to be the first additively manufactured engine piston made entirely from ceramic for its Chaos ultracar. Using technology from XJet, Rehovot, Israel, the lightweight ceramic piston and rod is said to offer extraordinary strength, hardness and resistance to thermal expansion.

The Chaos, which is currently in development, reputedly has the fastest-revving production car engine ever seen, reaching up to 12,200 RPM and 3,065 horsepower. The ultracar is expected to reach speeds of over 500 kph and acceleration from 0 to 100 kph in 1.55 seconds.

SPA founder Spyros Panopoulos explains that to make the engine a reality and support the extreme levels of performance required, the ‘anadiaplasi’ piston was designed. Anadiaplasi is Panopoulos’ proprietary name for the company’s generative design process in which a component takes its shape based on the forces acting on it. Material is minimised where it doesn’t support performance and added where reinforcement is needed, optimising weight while maintaining the strength and temperature resistance of the part – essential for any piston, but particularly testing in such a high-performing engine. The result is an organic complex shape that is both light and strong.

On concluding the design, Panopolous realised that to produce such complex geometry – along with the high accuracy and excellent surface finish required – the only relevant manufacturing technology was Additive Manufacturing. The company then selected XJet’s Nanoparticle Jetting technology and, in collaboration with XJet’s Greek business partner Lino 3D, selected XJet alumina material for the Chaos piston.

“Ceramic offers many advantages compared to other materials,” stated Panopolous. “Harder and stiffer than steel, more resistant to heat and corrosion than metals or polymers, and weighing significantly less than most metals and alloys. XJet’s alumina parts will withstand the high temperatures expected to develop within the combustion chamber as well as on the fast-moving parts.”

“XJet systems are uniquely capable of producing this part in ceramic, and there’s absolutely no room for error in this project,” he added.

An advocate of Additive Manufacturing, Panopolous is putting it to use throughout the Chaos Ultracar with a reported 78% of the body being additively manufactured, as well as other crucial elements such as the engine block, camshaft and intake valves.

“We are proud to be using such progressive technology in our Ultracar,” Panopolous added. “Our projects push performance to the extreme and so we are extremely selective about the materials and technologies we use. I believe this is the first-time ceramic AM is being used in motorsport and I feel privileged to take that pioneering step.”

Haim Levi, XJet VP Strategic Marketing, concluded, “SPA is taking ceramic Additive Manufacturing and Design for AM – DIAM – to the edge and beyond with their work on the Chaos Ultracar. We’re extremely proud to be part of such a trailblazing project by offering the top-level capabilities of our technology and system. Designers and engineers from a wide range of industries and applications are exposed to new options now opened for them. We expect the Chaos project ceramic piston to ignite their creativity and imaginations and push the limits in the automotive industry and beyond.”

www.xjet3d.com
www.spyrospanopoulos.com
Advanced Metalworking Practices (AMP) manufactures and supplies a wide range of both standard and custom-configured MIM feedstocks for your application. Contact Chris Chapman at cchapman@ampmim.com or 724-396-3663.
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www.erowa.com

Lithoz delivers CeraFab Multi 2M30 to non-profit Welsh research facility

Lithoz GmbH, Vienna, Austria, has delivered the UK’s first CeraFab Multi 2M30 machine to Compound Semiconductor Applications (CSA) Catapult, a government-backed research facility in Newport, Wales.

The CeraFab Multi 2M30 is an Additive Manufacturing machine that uses a Vat Photopolymerisation (VPP) process which the company calls Lithography-based Ceramic Manufacturing (LCM). The machine has two separate vats which can combine multiple materials — including ceramic, metal and polymer — within a single layer and can vary the material composition layer-by-layer.

“The CeraFab Multi 2M30 3D printer, part of the DER Investment in state-of-the-art equipment, is a valuable addition to our advanced semiconductor integration and packaging capability,” stated Dr Jayakrishnan Chandrappan, Head of Packaging at CSA Catapult, which helps optimise advanced electronic systems and delivers industrial research organisation to benefit companies in the UK. “This acquisition will help us develop novel 3D printed multi-material parts for high-power and high-frequency microelectronics packages, and the multi-material printing facilities will drive energy-efficient, compact and affordable packaging.”

CSA Catapult is a non-profit organisation focused on bringing compound semiconductor applications to life in three key areas: the road to Net Zero, future telecoms and intelligent sensing. The organisation works within the power electronics, RF & microwave and photonics technology areas and has an interest in advanced packaging. The organisation exists to help the UK compound semiconductor industry grow and collaborates across the UK and internationally.

www.lithoz.com
www.csa.catapult.org.uk

Compound Semiconductor Applications (CSA) Catapult is the recipient of the UK’s first CeraFab Multi 2M30 machine [Courtesy Lithoz]
Epson Atmix to establish recycling facility for metal powder production

Epson Atmix Corporation, Aomori, Japan, an Epson Group company, has announced plans to invest several billion yen to build and equip a new metal recycling facility. The company will process used metals from within Atmix, as well as external sources, to use as raw material for the production of its fine metal powders.

Atmix produces a range of metal powders for a variety of manufacturing processes, including Metal Injection Moulding and Additive Manufacturing. The company also produces magnetic powders for use in power supply circuits, as coils for IT equipment (e.g., smartphones), and for hybrid cars and electric vehicles.

The Epson Group has set a goal of becoming non-renewable resource-free by 2050. In addition to this, Atmix believes it necessary to establish a closed-loop metal powder manufacturing ecosystem to address potential issues with the future supply of metals, due to resource depletion and rising prices.

Atmix has stated that it plans to invest in an induction furnace for melting metals, refining equipment for removing impurities from metal, and a pig casting machine for forming ingots. The used metal will come from sources such as out-of-spec metal powder products in Atmix’s manufacturing process, metal waste from its factory, metal scraps and used moulds and dies discharged by Epson and others.

Operations are scheduled to begin in 2025 and within three years Atmix expects recycled metal materials to meet about 25% of its total raw metal material needs. This new Atmix factory is positioned as the first step toward becoming ‘underground resource-free’ and is expected to be a crucial part of Atmix’s efforts to develop a sustainable metal powders business.

www.atmix.co.jp
Elmet Technologies Inc, Lewiston, Maine, USA, reports that it has expanded the scope of its accredited practices at its analytical laboratory, having gained A2LA-accreditation for technical competence in the field of mechanical testing.

In addition to the A2LA-accreditation, this lab is also accredited in accordance with the recognised International Standard ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories. This demonstrates technical competence for a defined scope and the operation of a laboratory quality management system.

The lab’s accredited practices have included tensile testing, density testing, hardness testing (Rockwell and Vickers microhardness), as well as microstructure analysis and grain size measurements. Practices now covered by the ISO 17025 scope include chemical composition analyses using optical emission spectroscopy (ICP-OES) and carbon & gas analysis in metals using combustion analysis.

Elmet Technologies is a global leader in high-performance tungsten and molybdenum refractory metal product manufacturing and machining services. Its refractory metals expertise covers a range of pure metals (W and Mo) and alloys (TZM, MoLa, MoTa, WHA, WK, HCT) and serves a number of industries including defence, lighting, electronics, semiconductor, thin-film, automotive, aircraft and medical.

CMG Technologies, Woodbridge, Suffolk, UK, has invested more than £250,000 in a new ECM sintering furnace and 3DGence Additive Manufacturing machine. The investment will allow the company to bolster its Metal Injection Moulding services and newer ventures in Additive Manufacturing.

“We’re very excited to be able to expand on the technology we already have here at CMG,” stated Rachel Garrett, Managing Director of CMG Technologies. “Not only will the furnace be a beneficial addition to our MIM operations but it, along with the printer, will also support our growing 3D printing services.”

“This industry and the technologies involved are ever-evolving, so this new machinery will help us stay ahead of the curve and offer more support to our existing and new clients,” she continued.

Since late 2021, the company has been offering metal Additive Manufacturing services from initial design to post-processing of the product. The new technology is in addition to the four furnaces and four Additive Manufacturing machines already in use at the company’s factory.

Dr Samuel Wilberforce, Head of 3D Printing, added, “Additive Manufacturing is a complementary technology to our extensive MIM services. By using 3D printing, we can create prototypes and moving parts far quicker than traditional methods, while keeping waste to an absolute minimum.”

“Thanks to these additional machines, we will be able to offer more services to clients across the world – from design to printing, or just the post-processing of parts to create a dense metal end-product,” he concluded.

CMG Technologies has purchased a 3DGence Additive Manufacturing machine to support its MIM and AM (Courtesy CMG Technologies)

CMG Technologies has invested in a new ECM sintering furnace (Courtesy CMG Technologies)
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World PM2022  |  October 9-13  |  worldpm2022.com
World PM2022 Congress & Exhibition to showcase the global Powder Metallurgy industry

The technical programme for the World PM2022 Congress & Exhibition, organised and sponsored by the European Powder Metallurgy Association (EPMA), has been published and is now available to view online. Taking place in Lyon, France, October 9–13, 2022, the international event will feature a comprehensive programme of oral and poster presentations, as well as an exhibition showcasing the latest developments from the global Powder Metallurgy supply chain.

Held in Europe once every six years, the World Congress is an essential destination for the international PM community to gather and discover the latest technology innovations, as well as meet suppliers, producers and end-users.

The all-topic technical programme includes sessions covering Press & Sinter Powder Metallurgy, Metal Injection Moulding, Hot Isostatic Pressing (HIP) and metal Additive Manufacturing. It also focuses on powder production technologies, materials, post processing and end-use applications.

A number of awards will also be presented during the event, including the Powder Metallurgy Component Awards and Distinguished Service Awards, along with technical paper awards.

Early registration discount is available until September 8.

www.worldpm2022.com

PM China 2022 International Exhibition postponed due to pandemic

The 15th China International Exhibition for Powder Metallurgy, Cemented Carbides and Advanced Ceramics (PM China 2022), which was scheduled to take place at the Shanghai World Expo Exhibition Center from May 22 – 25, has been postponed due to COVID-19. The event will now take place November 4 – 6, 2022, at the same venue.

Uniris Exhibition Shanghai Co., Ltd., the organiser, stated, “Considering the current COVID-19 scenario in Shanghai, especially the priority of the health & safety of all attendees, in accordance with the related COVID-prevention regulations of Shanghai municipal government, we decided to announce the official postponement of 2022 China International Exhibition for Powder Metallurgy, Cemented Carbides and Advanced Ceramics (PM China & IACE China 2022) and concurrent activities (formerly scheduled on May 23–25, 2022 in Shanghai World Expo Exhibition Center), the specific date will be announced according to the COVID control situation.”

“We fully apologise for any inconveniences caused by the postponement due to the pandemic. We would like to express our sincere thankfulness to all exhibitors, visitors and partners for the constant attention, trust and support to the exhibition. We will be closely following the pandemic status.”

The organiser concluded, “At this critical moment of COVID prevention, thank you for your understanding and support, and we look forward to meeting you in a safe, wonderful and fruitful industry pageant in Shanghai soon.”

http://en.pmexchina.com/
MPIF releases 2022 edition of Standard Test Methods

The Metal Powder Industries Federation (MPIF) reports that the 2022 Edition of Standard Test Methods for Metal Powders and Powder Metallurgy Products is now available to purchase.

This new volume contains forty-eight standards covering terminology and recommended methods of testing for metal powders, Metal Injection Moulding parts, metallic filters, Powder Metallurgy equipment and metal Additive Manufacturing. The most current versions of these standards, which are used in the production of both metal powder and Powder Metallurgy products, are required by Quality Assurance programmes in order to maintain full compliance.

The 2022 edition includes the following three new standards:

- MPIF Standard 73: Preparing and evaluating tension test specimens of materials produced from metal powders by Binder Jetting (BJT), Material Jetting (MJT), Material Extrusion (MEX) or similar metal Additive Manufacturing technologies
- MPIF Standard 74: Preparing and evaluating tension test specimens of materials produced from metal powders by Laser Beam Powder Bed Fusion (PBF-LB) and Electron Beam Powder Bed Fusion (PBF-EB), Directed Energy Deposition (DED), and Cold Spray or similar hybrid metal Additive Manufacturing technologies
- MPIF Standard 75: Determination of flow rate of metal powders using the Carney Flowmeter Funnel

Additionally, an updated version of A Collection of Powder Characterization Standards for Metal Additive Manufacturing is now available which contains twelve existing MPIF Standard Test Methods that can be applied for the characterisation of powders used in metal AM processes.

www.mpif.org

In the world of metal powders, Höganäs is always at the forefront of innovation. From more sustainable production processes to new and patented powder compositions, we are dedicated to offering you the optimal solutions while reducing environmental impact. With forAM®, our range of metal powders designed for additive manufacturing, we can offer powders designed for any application.

The forAM® range includes nickel, iron, cobalt, copper, titanium and aluminium powders in a variety of grades and compositions. Combining optimal powder performance with improved sustainability is a priority for Höganäs. In addition to our material innovations, we have also committed to Science Based Targets and are founding members of the Additive Manufacturing Green Trade Association, demonstrating our ongoing commitment to leading sustainable transformation in our industry.

www.hoganas.com
Fraunhofer IFAM Dresden names Prof Thomas Weissgärber as its new director

Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM), Dresden, Germany, has appointed Prof Dr-Ing Thomas Weissgärber as its new director. Since April 1, Prof Weissgärber also holds the professorship of Powder Metallurgy at the Institute of Materials Science in the Faculty of Mechanical Engineering at Technische Universität Dresden.

Prof Weissgärber has been associated with the Dresden site of Fraunhofer IFAM for many years. During his career as a group and department head, as well as deputy and most recently interim head of the institute, he has conducted research in various areas of Powder Metallurgy. Within his work at the Innovation Center Additive Manufacturing (ICAM), he has established a knowledge base in the field of powder-based AM.

“Fraunhofer IFAM is one of Europe’s most important independent research institutes in the fields of adhesive technology, surfaces, shaping and functional materials. Its products and technologies primarily address industries of particular importance for the future viability of the economy, including energy technology, mobility and life sciences,” stated Prof Reimund Neugebauer, President of the Fraunhofer-Gesellschaft. “I am extremely pleased that Prof Thomas Weissgärber is now at the helm. He is a long-standing leader who has made a significant contribution to developing Fraunhofer IFAM into one of the leading applied research institutes in the field of powder metallurgical technologies and materials.”

Admatec offers increased capacity for ceramic AM production

Admatec, Goirle, the Netherlands, has introduced a new integrated debinding and sintering furnace, with an enlarged inner volume, in an effort to increase throughput and efficiency in technical ceramic Additive Manufacturing and post-processing. The company also announced it has increased the build volume of its Admaflex300 Vat Photopolymerisation (VPP) ceramic AM machine.

Since 2018, Admatec has offered a compact integrated debinding and sintering furnace, especially designed for post-processing of additively manufactured technical ceramics. After enlarging the build volume of the Admaflex machines to 260 x 220 x 500 mm, Admatec has introduced its integrated debinding and sintering furnace with an inner volume of 400 x 400 x 400 mm.

For a number of years, Prof Weissgärber has been helping to establish a close link between science and applied research, holding lectures on the topics of materials in energy technology, Powder Metallurgy and sintered materials, as well as thermophysical properties and high-temperature behaviour. Through the professorship for Powder Metallurgy, Sintering and Composite Materials at TU Dresden, he intends to further strengthen this alliance in the future.

“I consider my new role as a motivation to continue to develop and expand existing competences at Fraunhofer IFAM, and, together with my team, to use the excellent know-how, particularly in materials, Powder Metallurgy and Additive Manufacturing for innovative, future-proof developments in order to generate optimum solutions in core areas such as energy technology, mobility and medical technology,” stated Weissgärber.

www.ifam.fraunhofer.de

These adjustments, in combination with the specially designed integrated debinding and sintering furnaces, currently allow users to produce a set of additively manufactured technical ceramic parts, from CAD design to sintered end-use part, in fewer than seven days. With a maximum temperature of 1700°C and an inner volume of 64 litres, the new furnace has almost ten times the size of the original compact integrated furnace.

www.admateceurope.com

The increased build volume of Admatec’s debinding and sintering furnace is nearly ten times what was previously offered by the company (Courtesy Admatec)
Swedish heating technology company Kanthal, part of the Sandvik Group, and metals research institute Swerim, based in Luleå, Sweden, report that their ultra-modern atomising equipment designed for the production and development of metal powders is now operational following a previously announced joint investment of €2 million.

With a high degree of flexibility, the new equipment is specially designed for the research and development of both materials and the atomisation process for Additive Manufacturing and Powder Metallurgy applications. It is possible to atomise powder charges of up to 85 kg, suitable for AM, Metal Injection Moulding, surface coating and Hot Isostatic Pressing.

Swerim and Kanthal’s investment is said to be a result of the increased demand for research surrounding materials and process development within Additive Manufacturing and Powder Metallurgy sectors. The partnership will see a long-term collaboration, whereby Kanthal will gain access to Swerim’s expertise in Powder Metallurgy, Additive Manufacturing of metal products, advanced structural analysis, testing and modelling. Swerim will have the opportunity to build further on knowledge within these areas.

“This investment brings unique opportunities for customised development within Additive Manufacturing and it means that we can bring new materials to the market faster,” stated Dilip Chandrasekaren, Head of R&D at Kanthal. “Cooperation with Swerim also gives us the prerequisites for conducting world-class R&D within a strategic area for Kanthal and Sweden.”

Annika Strondl, manager of Powder Materials and Additive Manufacturing at Swerim, commented, “It’s fantastic that metals research institute Swerim and Kanthal are together investing 20 million kronor in a state-of-the-art atomiser unit. This has enabled a unique platform for R&D activities focussing on alloying and powder development for all of Sweden. The fact that we are investing together with the industry just goes to show that Swerim is an attractive research partner within powder and alloying development.”

www.kanthal.com
www.swerim.se
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Tel. +49(0)5403 3219041
E-mail: burkard@bmv-burkard.com

www.antai-emarketing.com
Tethon 3D and Showa Denko America develop high-purity alumina for ceramic Additive Manufacturing

Tethon Corporation Inc (Tethon 3D), Omaha, Nebraska, USA, has announced a collaboration with Showa Denko America, New York City, a subsidiary of global chemical company Showa Denko K.K., headquartered in Tokyo, Japan. The partnership has resulted in a high-purity alumina for ceramic Additive Manufacturing.

The alumina material, the first UV resin developed jointly by the two companies, has a ceramic loading of over 75% by volume and 90% by weight, which is reported to be 25% higher than competitor options. Due to this higher loading, shrinkage in the x, y and z axes is said to be less than 10% after sintering.

“It has been a pleasure working with the Showa Denko team. Tethon’s unmatched additive experience based around filled UV resins coupled with Showa Denko’s decades of experience in the inorganics, ceramics, and chemical sectors will revolutionise ceramic Additive Manufacturing,” stated Trent Allen, CEO of Tethon 3D. “Some ceramic additive solutions have issues with shrinkage which limit feature sizes and often create unwanted warpage. This material and partnership set a new standard around material properties and reflects the original intent of the ceramic Additive Manufacturing industry.”

Masao Horayama, president of Showa Denko America, added, “We are expecting to see a lot of growth in ceramic additive over the next decade, and our Showa Denko America team has been looking to enter the additive market. We are very excited to launch this first alumina material designed for additive and believe working with an experienced materials team like Tethon is an appropriate venue for bringing Showa Denko’s material expertise to market.”

www.tethon3d.com
www.showadenko.us

A part showcasing the high-purity alumina resulting from the collaboration between Tethon 3D and Showa Denko America (Courtesy Showa Denko KK)

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www.tethon3d.com
www.showadenko.us

A part showcasing the high-purity alumina resulting from the collaboration between Tethon 3D and Showa Denko America (Courtesy Showa Denko KK)
Metal Powder Emergence offers metal powders and consultancy services

Metal Powder Emergence Ltd (MPE), headquartered in London, UK, is a recently established business providing gas atomised metal powders for Additive Manufacturing, as well as Metal Injection Moulding, Hot Isostatic Pressing (HIP) and cold/thermal spray applications.

Before founding MPE, Dr Gordon Kerr, the company’s CEO, spent ten years at Phoenix Scientific Industries (PSI) where he worked with customers and collaborators developing VIM gas atomised powders for a range of applications and sectors.

“My experience over the past ten years has shown that it’s possible to supply high-quality additive metal powders at a cost which is more closely aligned with the client’s needs,” stated Kerr.

MPE is currently working with a key business partner to provide cost-effective, high-quality metal powders which are manufactured in accordance with ISO 9001. The powders are melted under a vacuum, which provides clean, free-flowing powders with high sphericity, vital for many AM processes.

“Generally, lead times are shorter compared to many other powder providers. All powders are requalified using third-party independent UK analytical service test houses which are also ISO 9001 compliant,” added Kerr.

Established alloy powders based on aluminium, cobalt chrome, copper, titanium, nickel superalloys, stainless steels (316L, 17-4PH) are available, as well as the supply of bespoke novel alloy compositions. Technical and manufacturing consultancy is offered to assist in the development of powder alloy compositions tailored to meet clients’ needs.

With a PhD in Chemistry from Heriot-Watt University in Scotland, Kerr has played a key role in European and UK funded projects with Innovate UK, Faraday and NATEP/ATI. He has previously held Managing Director positions and delivered growth within high-technology businesses, developing and implementing strategies to address various market and customer needs, as well as driving teams to common goals.

MPE can take a product from R&D scale to full-scale production manufacturing utilising marketing and sales expertise in order to meet a range of market needs. Kerr is primarily focused on developing novel AM materials for applications such as nanotechnology, responsive and smart materials for markets such as aerospace, marine, battery applications and space exploration.

MPE recently collaborated on new projects and applied for UK grant funding with a leading UK university in materials science and two well-established UK organisations.

www.metalpowderemergence.com
Nanoe and Kimya partner to bring metal and ceramic filaments for AM to North American market

Nanoe, headquartered in Ballainvilliers, France, and Kimya, an Armor Group company based in Nantes, France, announced a marketing partnership during the opening of AMUG which took place in Chicago in April, 2022. The partnership will bring Nanoe’s Zetamix filaments for ceramic and metal Additive Manufacturing to the North American market as part of Nanoe’s aim for international growth.

Founded in 2008, Nanoe specialises in the development and manufacture of innovative ceramic materials for industry. It is a recognised manufacturer of high-performance alumina and zirconia, as well as the world leader in ZTA composite ceramics. Zetamix is a brand of ceramic and metal filaments compatible with machines utilising Fused Filament Fabrication (FFF), a Material Extrusion (MEX) process. These filaments are reportedly able to withstand temperatures of up to 1600°C and are notably used in laboratory applications (specimen holders, crucibles, etc) and by industrial operators in a variety of fields, such as jewellery and aerospace.

Operating in the North American market since 2019, Kimya provides support to international industrial operators for their Additive Manufacturing projects requiring the production of finished parts, thanks to the design and production of bespoke 3D materials. The company also offers a range of ready-to-use filaments with specific chemical and mechanical properties. Through this partnership, the company is expanding its range with the addition of ceramic and metallic filaments.

“We are delighted to be expanding our distribution channels in strategic regions like North America thanks to our partner Kimya, with which we share a vision and the know-how in technical materials for the production of finished parts,” stated Guillaume de Calan, co-founder of Nanoe. “We are fully confident in its ability to represent our filament range in this market and to help us extend the use of ceramic and metallic Additive Manufacturing on the international stage.”

Pierre-Antoine Pluvinage, Business Development Director at Kimya, commented, “At Kimya, it is our goal to establish a long-term presence in the North American market. Already in 2020, we installed new semi-finished product cutting lines at our Armor USA premises, in order to better serve the specific demands of our American industrial customers. In 2021, North America accounted for 35% of the global 3D printing market, estimated to be worth $17 billion. This is why we are determined to establish even stronger local roots, notably by now extending our range of 3D materials with the Zetamix by Nanoe filaments. These hi-tech materials complement our own range, providing solutions for the production of finished parts via Additive Manufacturing.”

www.zetamix.com
www.kimya.fr

APG posts design guide for Metal Injection Moulding

Alpha Precision Group (APG), St Mary’s, Pennsylvania, USA, a company that provides conventional Powder Metallurgy, high-temperature stainless steel PM, Metal Injection Moulded and additively manufactured components, has published a blog post outlining a design guide for Metal Injection Moulding.

The guide provides an overview of the chief design criteria to be considered in order to meet quality requirements. This includes:

- Part orientation
- Gate positioning
- Witness marks
- Surface
- Draft angles
- Sag effect
- Wall thickness
- Surface area
- Corner breaks & fillets
- Holes & slots

APG is comprised of five manufacturing plants located in Pennsylvania and Michigan, with over 400 team members, and was acquired by Nichols Portland, Inc, headquartered in Portland, Maine, USA, earlier this year.

www.alphaprecisionpm.com
Unique inert gas atomizing technology produces highly specified, spherical metal powders for MIM and AM applications. Team with history of developing and producing fine gas atomized powders since 1990.

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With partner Novamet Specialty Products Corp., Ultra Fine provides various after treatments, coatings and other capabilities using Ultra Fine’s high quality powders.
Ipsen USA finishes record Q1 with twenty-two new vacuum furnace orders

Following a record year for new equipment orders in 2021, Ipsen USA, Cherry Valley, Illinois, USA, has reported that its Vacuum Technology Excellence Center confirmed twenty-two new vacuum furnace orders and record part bookings during the first quarter of 2022.

“We continue to see improved business levels in all target markets, driven by the need for additional production capacity along with customer requests for more unique thermal process capabilities,” stated Patrick McKenna, president and CEO, Ipsen USA.

Vacuum furnace orders were said to have spanned several industries including automotive, Additive Manufacturing, aerospace, commercial heat treating and tool & die. Ipsen also reported a wide variety in ordered furnace models, from large vertical bottom loading units for aerospace to small vacuum debind and sinter furnaces for Additive Manufacturing. Other orders included those for Ipsen’s AvaC® low-pressure carburising capability, as well as high-pressure gas quenching used in conjunction with vacuum compression brazing.

Ipsen also stated that it was on track for a record year in aftermarket services; in Q1, Ipsen performed over 250 field service visits related to installation and start-up, furnace relocation, hot zone replacement, preventative maintenance, calibrations and leak checks.

“Our aftermarket business is strong and only getting stronger,” stated John Dykstra, Chief Service Officer, Ipsen. “We continue to add resources to the team and complete strategic initiatives designed to improve response times and reduce downtime for our customers.”

In addition to the growing demand for new equipment and aftermarket support, Ipsen hired twelve new employees.

www.ipsenusa.com

Parmaco to promote Metal Injection Moulding through MIM Roadshow

Parmaco Metal Injection Moulding AG, a MIM producer based in Fischingen, Switzerland, is to hold a series of seminars as part of its MIM Roadshow. Taking place between July and November 2022, the five MIM seminars will be held at multiple locations across Germany, Switzerland and Austria.

Parmaco produces a wide range of MIM and microMIM components and assemblies for various applications and markets worldwide. The company manufactures MIM components for diverse sectors, including medical technology, automotive industry, machine engineering, electronics, locking systems and aerospace engineering.

The current schedule for the MIM Roadshow is as follows:
- July 27 – Parmaco MIM Seminar DE, Regensburg, Germany
- September 30 – Parmaco MIM Seminar DE, Fischingen, Switzerland
- October 19 – Parmaco MIM Seminar DE, Leipzig, Germany
- November 8 – Parmaco MIM Seminar DE, Troisdorf, Germany
- November 22 – Parmaco MIM Seminar DE, Vienna, Austria

In addition to its MIM Roadshow, Parmaco offers training courses for customers and partners at its Fischingen facility.

www.parmaco.com
Formnext + PM South China scheduled for September

The second Formnext + PM South China, jointly organised by Guangzhou Guangya Messe Frankfurt Co Ltd and Uniris Exhibition Shanghai Co Ltd, is scheduled to take place from September 14 – 16, 2022, at the Shenzhen World Exhibition and Convention Center. Covering advanced technology and equipment categories including materials, Additive Manufacturing, Powder Metallurgy, advanced ceramics, design, software and processing technologies, the fair is intended to act as a melting pot for information exchange.

In addition to the confirmed exhibitors from the Additive Manufacturing and Powder Metallurgy sectors, the organisers of Formnext + PM South China will introduce the first ‘Start-up Area’ at the Shenzhen event. This area is intended to support start-ups who have been in the market for fewer than five years, offering newly established firms the chance to get in touch with the broader community while serving as an effective marketing tool to grow their networks and promote their products and technologies.

A series of concurrent events will be held during the fair, including the following:

- The 2nd New Energy Vehicle Additive Manufacturing Application Industry Summit
- The 4th South China Injection Moulding and Additive Manufacturing Technology and Application Summit
- The 2nd Discover 3D Printing – ACAM
- The 2nd Shenzhen International Ceramic 3D Printing Application Summit
- The 2nd 3D Printing Application Conference – Powered by UNLANDS
- Advanced Ceramics Summit
- Formnext + PM South China Product Launch Conference

Formnext + PM South China forms part of a series of international events including Asiamold and Formnext. Asiamold will be held from March 1 – 3, 2023. The next edition of Formnext will be held from November 15 – 18, 2022, in Frankfurt am Main, Germany.

More information about Formnext + PM South China is available via the event website.

www.formnext-pm.com

Formnext + PM South China will take place at the Shenzhen World Exhibition and Convention Center (Courtesy Messe Frankfurt)

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hard metals

Vol. 16 No. 2 © 2022 Inovar Communications Ltd
Tritone moves headquarters to accommodate future expansion

Metal and ceramic Additive Manufacturing provider Tritone Technologies has announced its move to a new office in Rosh-Ha’ayin, Israel. The new office is intended to provide increased capacity for research & development, marketing, customer support, engineering and a new showroom.

Tritone’s Additive Manufacturing portfolio is based on the company’s MoldJet® technology, incorporated in its Dominant and DIM Additive Manufacturing systems. Since its introduction, Tritone has increased its set of available metal and ceramic materials to address the rigorous requirements of industrial applications. Enhancements have included advanced verification of print quality, precision and uniformity, higher throughput, and improved streamlined post process of parts.

“We were fortunate to find such a nice and large space located near our previous offices in the central area district of Israel,” stated Ronen Braunstein, COO of Tritone Technologies. “In the upcoming months, we will lease additional space for our lab support and machinery. Our new location will help our company to expedite growth and to give our employees a better working environment and experience. It will also help us stay in line with the current needs of showcasing our machines through online technologies, as things have shifted due to the COVID-19 pandemic where businesses had to become more accommodating to change.”

www.tritoneam.com

Lithoz reports strongest first quarter in its history

Lithoz GmbH, Vienna, Austria, has reported its strongest start to a new business year, with eight machines sold since the beginning of 2022. With these sales, Lithoz’s LCM ceramic Additive Manufacturing machines are now installed in over twenty-five different countries, highlighting the global growth of ceramic Additive Manufacturing as an established process.

The company’s range of Additive Manufacturing machines – including the CeraFab System, CeraFab Lab L30 and CeraFab Multi 2M30 – cover the entire spectrum of manufacturing needs and may bring opportunities to companies with research & development. The CeraFab Lab L30, its latest launch, is intended to make ceramic Additive Manufacturing more accessible for new adopters, while the CeraFab Multi 2M30 enables multi-material Additive Manufacturing.

The company recently brought its technology to Africa for the first time with the government-backed installation of a CeraFab Lab L30 at the Central University of Technology in South Africa. This latest installation, as well as a recent installation in the UK for the first time, is said to highlight the company’s growing global expansion and forecasts a very successful year for the company.

www.lithoz.com
Ultra Safe Nuclear Corporation adds Desktop Metal’s X-Series Binder Jetting to make SiC parts for nuclear energy sector

Desktop Metal, headquartered in Boston, Massachusetts, USA, reports that Ultra Safe Nuclear Corporation (USNC), headquartered in Seattle, Washington, USA, a developer of Micro Modular Reactor (MMR) systems for the production of nuclear energy, has added two Binder Jetting (BJT) machines from Desktop Metal’s X-Series line, with two further machines to follow this year.

Desktop Metal’s recently rebranded X-Series line of BJT machines for metal and ceramic powders — which includes the InnoventX, X25Pro and X160Pro — can additively manufacture advanced materials such as silicon carbide (SiC), a technical ceramic with extreme environmental stability often used in aerospace, armour, plasma shield and high-temperature applications.

USNC transforms highly pure, crystalline, nuclear-grade SiC into the shapes and forms that can safely surround a nuclear fuel particle, enabling USNC’s Fully Ceramic Micro-encapsulated (FCM) fuel innovation. The technology is said to be a key component of USNC’s innovative fuel design for use in a new generation of advanced reactors.

“Binder Jetting is a low-cost, high-yield, reliable process for our complex serial production,” stated Dr Kurt A Terrani, executive vice president of USNC’s Core Division. “The advanced material capability of the X-Series machines is fundamental to our innovative approach to fuel design.”

The X-Series line was designed to scale applications from research and development to mass production with repeatable open parameters and performance across a range of machines. With the small-format InnoventX already installed at the company’s facility in Salt Lake City, Utah, USNC has developed its next-generation nuclear fuel matrix to be scaled up on the larger X25Pro and X160Pro systems.

Ric Fulop, co-founder and CEO of Desktop Metal, commented, “Driving mass adoption of Additive Manufacturing requires scalable systems capable of printing high-performance materials that enable the most innovative applications. We’re proud to support the mission of USNC with flexible Binder Jetting technology that takes customers all the way to production and helps play a role in solving global-scale problems with Additive Manufacturing solutions.”

www.desktopmetal.com
www.usnc.com
Researchers develop abrasion-based process for producing metal powders

A team of researchers at the Indian Institute of Science (IISc), led by Koushik Viswanathan, Assistant Professor at the Department of Mechanical Engineering, have reportedly identified an alternative technique to produce metal powders using an abrasion-based process.

Metal powders are predominantly produced using atomisation. However, despite its widespread use, explains the IISc researchers, atomisation returns poor yield, is relatively expensive and limited in the types of materials. The alternative technique developed by the researchers is said to side-step these problems.

In the metal grinding industry, the material removed – known as swarf – is often discarded as a waste product. It is commonly stringy in shape, like metal chips, but can also include perfectly spherical particles. Scientists have long theorised that these particles go through a melting process, which results in the spherical shape. But this raises some interesting questions, such as whether the heat from the grinding causes the melting, or if there is actually any melting at all?

Viswanathan’s team has shown that these powder metal particles do indeed form as a result of melting due to high heat from oxidation, in an exothermic reaction at the surface layer. The team refined this process to produce large quantities of spherical powders, which are further processed to be used as stock material in Additive Manufacturing. The study is said to illustrate that these powder particles perform just as well as commercial gas atomised powders, when used in metal Additive Manufacturing.

Priti Ranjan Panda, a PhD student at IISc’s Centre for Product Design and Manufacturing and one of the authors of the study, commented, “We have an alternative, more economical and inherently scalable route for making metal powders, and the quality of the final powders appear to be very competitive when compared with conventional gas atomised powders.”

Regarding the applications of their findings, Viswanathan added, “There has been significant recent interest in adopting metal AM because, by nature, it enables significant customisation and allows design freedom. However, the large cost of stock metal powders has been the stumbling block. We hope that our work will open new doors to making cheaper and more accessible metal powders.”

Harish Singh Dhami, a PhD student at the Department of Mechanical Engineering and co-author of this study, noted, “Reducing the cost of the AM process [via economical powders] can widen the range of materials in situations such as manufacturing of biomedical implants, which could become cheaper and more accessible.”

The researchers reported that making metal powder using abrasion also has potential in other high-performance applications such as in aircraft engines, where a high degree of specification is required.

The full paper, titled ‘Production of powders for metal Additive Manufacturing applications using surface grinding,’ by Harish Singh Dhami, Priti Ranjan Panda, and Koushik Viswanathan, was published in Manufacturing Letters, Volume 32, 2022, ISSN 2213-8463 iisc.ac.in
ECerS announces ceramic sintering Summer School in Kraków

The ECerS Summer School is scheduled to be held before the Ceramics in Europe conference and exhibition from July 8–9 in Kraków, Poland. This year’s course topic will be ‘Fundamentals and Advanced Technologies of Sintering.’

Presented by recognised experts in the field, the ECerS Summer School will consist of ten modules:

- Overview of the fundamentals of sintering
- Toolbox to control grain growth during densification of ceramics
- Miracle versatility of advanced Si₃N₄: from engineering to functional applications
- Contrasting microstructure and densification processes during solid state and liquid phase sintering of Al₂O₃
- Fundamentals and technology of hot pressing and hot isostatic pressing
- Microwave sintering: what can it and can’t it do?
- Spark Plasma Sintering – design of experiments
- Flash sintering – towards faster, cheaper, greener and better ceramics
- Utilising cold sintering in the design and integration of new functional composite materials
- Impact of high heating rates: from pit firing to ultrafast high-temperature sintering

The ACerS Ceramic and Glass Industry Foundation (CGIF) is offering grants of $1,000 in travel funding for those interested to attend the summer school. Applications are open for undergraduate, graduate and PhD students.

www.ecers.org

Short course on Atomisation for Metal Powders to return in October

After a thirty-month COVID-induced delay, UK-based Atomising Systems Ltd and CPF Research Ltd have announced the return of the popular short course Atomisation for Metal Powders. The event is scheduled for October 6–7, 2022, in Manchester, UK.

The two-day course will consist of presentations from Atomising Systems’ John Dunkley, chairman; Dirk Aderhold, Technical Director and Tom Williamson, Research & Development Manager, as well as Andrew Yule, Emeritus Professor at the University of Manchester.

The course combines up-to-date practical information with theory and is expected to be of value to engineers working in both metal powder production and R&D. The organisers have expanded the event’s coverage of powder manufacture and properties for Additive Manufacturing.

www.atomising.co.uk
www.cpfresearch.com

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US President Biden launches initiative to boost Additive Manufacturing

US President Joe Biden has announced a new initiative aimed at improving US domestic supply chain resilience by focusing on Additive Manufacturing. The AM Forward programme aims to encourage large companies to source additively manufactured parts from smaller US-based suppliers. The voluntary compact is open to any OEM provided they are willing to make public commitments to support their suppliers’ adoption of additive capabilities. Thus far, GE Aviation, Honeywell, Lockheed Martin, Raytheon and Siemens Energy have joined the initiative.

The initiative will be supported by the non-profit Applied Science & Technology Research Organization (ASTRO). In a White House statement, the Biden Administration highlighted plans to launch federal programmes to help small- and medium-sized manufacturers support the adoption of adequate capacity and increase competitiveness through access to capital, technical assistance, and workforce training.

To fully benefit from the use of AM capabilities, it was stated, SME manufacturers must train their workforce differently to successfully deploy AM technologies, including upskilling workers. For this, America Makes will develop a curriculum for workforce training with AM Forward participants and, along with the US Department of Labor, will assist manufacturers in launching apprenticeship programs in AM.

“We are honored to be a part of this new initiative,” stated America Makes’ Executive Director John Wilczynski. “As America Makes continues to build the foundation for the acceleration of Additive Manufacturing, the AM Forward program represents a proof of concept for the original vision of the institute – to utilise the public-private partnership model in collaboration with private sector innovation to propel advanced manufacturing industries forward.”

The need for defining industry standards was also highlighted. It was added that the US Department of Commerce – through the National Institute of Standards and Technology (NIST) – will conduct measurement science research to overcome key barriers to the widespread use of metal AM. It will develop the technical basis for new high-priority standards, and disseminate these results to AM Forward participants through the leadership of standards development within ASTM International, International Organisation for Standardisation (ISO), American Society of Mechanical Engineers (ASME), and other standards bodies. www.whitehouse.gov

Call for presentations issued for MIM2023 conference

The Metal Powder Industries Federation (MPIF) has announced a call for presentations for MIM2023: International Conference on Injection Molding of Metals, Ceramics and Carbides, which is scheduled to be held at the Hilton Orange County/ Costa Mesa Hotel, California, USA, February 27-March 1.

Sponsored by the Metal Injection Molding Association, a trade association of the MPIF and its affiliate APMI International, the conference aims to gather product designers, engineers, end-users, manufacturers, researchers, educators, and students for technology transfer.

Presentations are invited on the following topics:

Manufacturing Innovations
- Part Design
- Tooling
- Moulding
- Debinding
- Sintering

Material Advancements
- Ferrous metals & alloys
- Non-ferrous metals & alloys
- Ceramics
- Hardmaterials
- Magnetics

Authors wishing to present a paper on manufacturing innovations and material advancements at MIM2023 have until September 30, 2022, to submit an abstract. Abstracts should be submitted using the submission form available on the conference website. All accepted abstracts will require a PowerPoint submission prior to the conference.

www.mim2023.org
HP and Legor Group collaborate on jewellery and fashion accessories

HP Inc., Palo Alto, California, USA, and Legor Group SPA, Vicenza, Italy, have announced a strategic collaboration for the development of innovative precious metal materials for HP’s Metal Jet system. Legor, a leader in metals science and production of alloys, powders, and plating solutions, is the first to produce speciality precious metal materials for the jewellery and fashion accessories markets designed to work with HP’s metal Binder Jetting (BJT) platform.

“Our vision for Additive Manufacturing goes beyond small series and prototyping,” stated Massimo Poliero, president & CEO of Legor Group SPA. “We see a future where every modern business will have one or more of HP’s state-of-the-art Binder Jetting printers in its facilities, enabled by Legor’s technology, design and support to reduce the time to market for both precious and non-precious metal parts. This strategic partnership with HP is the keystone to accelerate this vision and move the industry toward more sustainable manufacturing.”

“Our work with Legor aligns perfectly with HP’s vision to disrupt manufacturing norms, accelerate digital manufacturing and sustainable impact for customers around the world,” added Didier Deltort, president, HP Personalisation & 3D Printing. “The combination of our breakthrough Metal Jet 3D printing platform with Legor’s materials expertise and customer-centric approach will disrupt the luxury jewellery and fashion industries. This is an exciting milestone as we prepare to make Metal Jet more broadly available to the market later this year.”

The collaboration will initially focus on enabling the production of functional stainless steel accessories for the jewellery and fashion markets. In parallel, the companies will implement an R&D programme to parameterise and characterise bronze and silver powders and eventually gold powders, the core material in the precious sector.

HP and Legor will work to optimise the printing and sintering parameters for these new materials and the surface finish results. The research will take place in the new Legor 3DMetalHub in Bressanvido, Italy, a centre of excellence focused on accelerating Additive Manufacturing for the luxury industry.

www.legor.com
www.hp.com

Components built with the HP Metal Jet machine (Courtesy HP)
Desktop Metal offers sterling silver for jewellery and luxury goods sectors

Desktop Metal, headquartered in Boston, Massachusetts, USA, has qualified 925 sterling silver for use on its Production System, including the P-1 and P-50. The addition of the popular precious metal will enable manufacturers of jewellery and luxury goods to directly additively manufacture high-quality jewellery, watches, and decorative hardware.

The company also announced that it is fast-tracking the development of additional precious metal alloys, including 18K yellow gold, with active research and development also underway on rose gold.

“The qualification of precious metals for direct 3D printing on high-speed Binder Jetting systems is a major milestone for the jewellery and luxury goods industry,” stated Ric Fulop, founder and CEO of Desktop Metal. “All the design freedom and customisation of 3D printing can now be delivered directly at high volumes without all of the labour associated with traditional manufacturing processes. What’s more, this new direct 3D printing innovation builds on the established legacy of our ETEC brand, which has been a leader in 3D printers for lost-wax casting models for more than a decade — making us the unparalleled leader in comprehensive Additive Manufacturing solutions for the jewellery and luxury goods market.”

To advance the technology and materials needed to bring Additive Manufacturing’s quality, productivity and economics to the demanding luxury goods and jewellery market, Desktop Metal is partnering with Formula 3D Corporation (for the US market) and Neoshapes (international). Both of these collaborations aim to enable the luxury goods and jewellery markets to adopt metal Binder Jetting processes to produce end-use parts in precious metals, steels and more.

Formula 3D Corporation, Monrovia, California, USA, offers designers and manufacturers a complete end-to-end solution for additively manufacturing precious metals. A video was released with Formula 3D founder Christian Tse showcasing the use of Desktop Metal’s P-1 to create jewellery.

“Desktop Metal’s Production System adds extraordinary value to our existing jewellery manufacturing processes, increasing efficiency of production, getting new designs to market faster, and offering our customers greater versatility and multiple styling options. We can actually print in precious metals in two hours what we do in two days with casting,” added Christian Tse. “In addition, creating jewellery with Binder Jetting is allowing us to consider new options to circumvent some of the supply chain challenges facing the fine jewellery industry. We can bypass shipping delays and mounting costs, as well as avoid duties, by printing the precious silver directly, as opposed to shipping the physical metal.”

Neoshapes, based in Geneva, Switzerland, founded by experienced executives in the luxury goods industry, is said to offer a unique end-to-end approach, from the production and supply of powder, to the Additive Manufacturing and post-processing of precious metal components, as well as consultancy services to enable industry players to transition production processes to Binder Jetting technology.

“Binder Jetting opens up new perspectives for the luxury industry, even more now with the qualification of precious metal alloys, giving further leverage to develop and produce creative products from a single file, leaping forward into the digital supply chain,” stated Stéphane Vigié, Neoshapes co-founder. “The time to market for new creative products is also reduced considerably, allowing brands to better meet demand while maintaining minimal inventories.”

www.desktopmetal.com

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XJet announces new CEO and CFO as it focuses on company growth

XJet Ltd, Rehovot, Israel, has announced that Hanan Gothait, founder and CEO of the company, is stepping down from the role of CEO and will take up the position of president. Yair Alcobi will take on the role of CEO and is joined in the management team by Orit Tesler Levy who takes the position of CFO.

With its ceramic Additive Manufacturing technology established and its metal AM system now commercially available, XJet anticipates a significant ramp up in business over the next few years. The company explains that with his broad business experience, Alcobi will steer the company through this demanding period with the support of Avi Cohen who joined XJet as executive chairman of the board last year.

In previous roles as president of the PCB Division of KLA and president of Orbotech East Asia Subsidiary, Alcobi has a record of expanding revenues and profits. He grew division revenues significantly, doubling the operating profit.

“It has been a comprehensive process to search for a new CEO for XJet,” stated Cohen. “We interviewed and considered many candidates before making our decision. Yair’s record in scaling businesses is enviable and exactly the right fit for taking XJet to the next level. We have exciting times ahead and I am sure that Yair has what it takes to make XJet successful. I look forward to working closely with Yair.”

Gothait added, “I am very excited about Yair’s joining and looking forward to working closely with him. As a veteran of the industry, I am a big believer in XJet, its team, the technology and products. As a result, I’m delighted to continue with the company in the position of president and I look forward to assisting Yair in leading XJet to success.”

Alcobi will be supported by Tesler Levy, who comes to XJet in the role of CFO with experience from Applied Materials in Israel and Silicon Systems Segment in California, USA. Levy also has industry experience following a previous role as VP Finance FP&A Business Partnering at Stratasys.

www.xjet3d.com
MIM Ti6Al4V feedstock used in piston-based material extrusion for small batch size parts

Additive Manufacturing can be a cost effective and quick way of producing functional prototypes or small batch size green parts, using powder-binder formulations similar to those used in MIM feedstock. An example is the polymer-based Material Extrusion (MEX) process Fused Filament Fabrication (FFF), where typical MIM feedstock formulae can be adapted to filament requirements such as sufficient flexibility for spooling by adding elastomers or amorphous polyolefins. However, to keep changes to debinding and sintering of the additively manufactured green parts as low as possible, the use of highly filled filaments is not preferable for the complementary use of MEX in MIM process chains.

Now, researchers at the Fraunhofer Research Institution for Additive Manufacturing Technologies (IAPT), in conjunction with the Institute of Laser and System Technologies (iLAS), both based in Hamburg, Germany, have developed a new, low-cost piston-based Material Extrusion process (also known by them as PEX), which is said to be a complementary shaping process in MIM because, unlike FFF, it can use unmodified MIM feedstock to produce low-volume parts or prototypes. A paper outlining the PEX process for MIM Ti6Al4V feedstock was published in Materials, Vol. 15, 351, January 2022, pp. 19.

The authors of the paper – L Waalkes, J Längierich, P Imgrund, and C Emmelmann – stated that the PEX process could open up opportunities for small batch production (< 100 pieces/year) for sectors such as medical, aerospace and consumer products. PEX could also make available the rapid production of functional prototypes, which would significantly reduce the cost of the MIM product development process. They further stated that there are sectors where low-volume, high-end products, such as bespoke bicycle parts or parts for mountaineering equipment, could use the PEX process particularly where the high cost of MIM moulds would make low-volume part production too expensive.

In their research, the authors focused on processing unmodified commercially available feedstock, which comprises 66 vol.% spherical Ti6Al4V alloy powder with particle size distribution D90 = 19 µm, mixed with a proprietary binder system with paraffin wax as the main polymer component. The calculated density of the multi-component feedstock system is 3.23 g/cm$^3$.

The piston-based extrusion process takes place – analogous to low-cost FFF printers – with the aid of a stepper motor-driven gear drive (Fig. 1), which is reduced (130:1) by two gears to ensure precise control per step. The granular MIM feedstock is filled between the piston and the nozzle (capacity: 105.3 cm$^3$) and is completely melted by the heating elements. Subsequently, the molten material is compacted and extruded through the nozzle by a downward movement of the piston at a defined speed. The extruded feedstock is deposited on a print platform according to the cross-section of the part to be generated. A kinematic system moves the print platform in x-, y-, and z-directions so that acceleration of the extruder’s high mass is avoided. After depositing a layer, the build platform is lowered by one layer height and new layers.

![Diagram](Fig. 1) (a) Image of the PEX system used to produce green parts; (b) cross section of the piston extruder as CAD design. (From paper: ‘Piston-based Material Extrusion of Ti-6Al-4V Feedstock for Complementary use in Metal Injection Molding’, by L Waalkes, et al. Materials, Vol 15, 351, 19 pp)
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are deposited until the green part is completely built up.

The authors stated that an existing PEX system, equipped with strain gauges and calibrated on the basis of a theoretical model of piston extrusion, allowed the use of low-cost FFF product architectures in terms of software and hardware. In addition, they stated that pistons are easier to clean than complex screw geometries, which allows quick material changes. With the help of the in-process measured values, the authors reported that this approach allowed material-specific process parameters to be derived for an industrial grade Ti6Al4V MIM feedstock to produce dense green parts with comparable material properties in the sintered state to conventionally produced MIM parts.

In determining the required values for the PEX process, the authors first determined feedstock mass flows experimentally for a defined time, temperature, and force interval. From this, a process window was derived, which was investigated with the help of test specimens. A fracture surface analysis of the test specimens was carried out to evaluate the resulting green part density. It was found that an extrusion force of 1300 N at a maximum build speed of 8 mm/s, in combination with an extrusion temperature of 95°C, resulted in sufficiently dense green parts. The identified process parameters thus...

Fig. 2 Schematic representation of the influence of the extrusion force on the green part density at a defined build speed, extrusion temperature and flow rate of 100%. (From paper: ‘Piston-based Material Extrusion of Ti-6Al-4V Feedstock for Complementary use in Metal Injection Molding,’ by L Waalkes, et al, Materials, Vol 15, 351, 19 pp)
closed the rhomboid voids (caused by under-extrusion) in the green parts whilst maintaining dimensional stability. Fig. 2 shows the influence of extrusion force on green part density and dimensional stability. For successful processing of the MIM Ti6Al4V feedstock using PEX, state 3 (Fig. 2) must be attained.

It was also found that density values (max. 99.1%) only deviate from the MIM reference by a maximum of 0.6%, which is still 2.4% above the minimum of ASTM F2885-11 (Table 1). Furthermore, it was shown that the build orientation has a decisive influence on the tensile and yield properties (also shown in Table 1), which the authors attributed to the PEX-related pores. The authors reported max. ultimate tensile strength of 1000 MPa, max. yield strength of 933 MPa, and max. elongation at fracture of 18.5% – depending on the selected build orientation. However, flat orientated test specimens were found to deviate only slightly from the MIM reference (YS: +33 MPa, UTS: 0 MPa, ε: −1.5%) and also meet ASTM F2885-11 with regard to minimum tensile properties.

Thus, the authors reported that the complementary use of PEX in the established MIM process chain could be proven in principle using MIM Ti6Al4V feedstock (Fig. 3). However, further research is to be carried out to accurately predict shrinkage of PEX additively manufactured green parts in order to ensure dimensional accuracy for different geometries.


<table>
<thead>
<tr>
<th>Specimens</th>
<th>Density [%]</th>
<th>Tensile properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>YS [MPa]</td>
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<tr>
<td>ASTM F2885-11</td>
<td>min. 96*</td>
<td>min. 680</td>
</tr>
<tr>
<td>MIM reference</td>
<td>99</td>
<td>900</td>
</tr>
<tr>
<td>Flat</td>
<td>99.1</td>
<td>933</td>
</tr>
<tr>
<td>Side</td>
<td>98.8</td>
<td>831</td>
</tr>
<tr>
<td>Vertical</td>
<td>98.4</td>
<td>866</td>
</tr>
</tbody>
</table>

*as-sintered

Table 1 Comparison of the AM specimens in orientation flat, side, and vertical with ASTM F2885-11 and MIM reference in terms of part density and tensile properties. (From paper: ‘Piston-based Material Extrusion of Ti-6Al-4V Feedstock for Complementary use in Metal Injection Molding’, by L Waalkes, et al. Materials, Vol 15, 351, 19 pp)
**NiAl-base alloy parts produced by Metal Injection Moulding**

Intermetallic compounds containing aluminium, such as NiAl, offer new opportunities for developing low-density, high-strength structural alloys for aircraft engines, which might be used at temperatures higher than is currently possible with conventional nickel-base superalloys. The addition of high-content alloying elements such as Cr, Mo and Zr into NiAl intermetallics further results in the formation of NiAl–Cr(Mo), and NiAl–Cr(Mo)Zr eutectic alloys, which allows not only a reduction in weight of many key components used in new generation supersonic aircraft engines, but, at the same time, provides sufficiently high strength and stiffness at high engine operating temperatures (1000–1100°C), good creep resistance and excellent corrosion and oxidation resistance.

However, despite the significant improvements to the strength of NiAl-base intermetallic alloys at high temperatures, there is little effect on the plasticity and fracture toughness at room temperature, which makes fabricating complex shapes by conventional methods such as machining difficult and costly. This has resulted in restricted commercial applications of such alloys and there is, therefore, an urgent need to adopt new production methods in order to overcome costly fabrication issues. Researchers at the School of Materials Science and Engineering and the National Key Laboratory for Precision Hot Processing of Metals, both located at the Harbin Institute of Technology, Harbin, China, have been studying the use of MIM as a suitable and cost effective alternative to overcome fabrication issues for mass production of complex shapes from NiAl-alloys. A paper outlining the results of their work has been published in *Powder Metallurgy*, Vol. 65, No. 1, 2022, pp. 52–60.

The authors, Bao Wang et al, reported that spherical NiAl–Cr,Mo,Zr pre-alloyed powders with particle size smaller than 30 µm were produced by gas atomisation. The nominal chemical composition of the powders is Ni–33Al–28Cr–5.5Mo–0.5Zr (at.%). The MIM feedstock comprised 62 vol.% alloy powders mixed with 38 vol.% paraffin-based binder system (69 wt.% high-density polyethylene, 29 wt.% paraffin wax, and 2 wt.% stearic acid). The MIM feedstock was injection moulded at 100 MPa and nozzle temperature of 160°C to produce sample cuboidal shapes (44 × 6 × 4 mm) and cylindrical shapes (diam. 20 × 6 mm). The cuboidal samples were used for shrinkage measurement and the cylindrical samples were used for compression.
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<table>
<thead>
<tr>
<th>Material Options</th>
<th>SS 17-4PH</th>
<th>SS 316</th>
<th>Tool Steel M2</th>
<th>4140</th>
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</thead>
<tbody>
<tr>
<td>Build Constraints</td>
<td>~ 300 gms weight max, footprint equivalent of a baseball, 0.04” minimum wall thickness</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Quantity</td>
<td>10<del>50 samples now. 500</del>5000 lots by mid-2022</td>
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<tr>
<td>Others</td>
<td>Tolerance within 2%, Finish 2 Ra max.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Industry News

Table 1 Physical properties of NiAl-(Cr,Mo,Zr) alloys prepared by MIM and sintered at different temperatures and holding times. (From paper: ‘Study of NiAl-based alloy parts produced by metal injection moulding’, by Bao Wang et al. Powder Metallurgy, Vol. 65, No. 1, 2022, 52-60)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Temperature (°C)</th>
<th>Holding time (h)</th>
<th>Relative density (%)</th>
<th>Shrinkage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1360H3</td>
<td>1360</td>
<td>3</td>
<td>85.76±0.04</td>
<td>6.62±0.05</td>
</tr>
<tr>
<td>1370H3</td>
<td>1370</td>
<td>3</td>
<td>90.48±0.05</td>
<td>10.61±0.03</td>
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<tr>
<td>1390H3</td>
<td>1390</td>
<td>3</td>
<td>95.83±0.08</td>
<td>14.93±0.06</td>
</tr>
<tr>
<td>1400H3</td>
<td>1400</td>
<td>3</td>
<td>92.96±0.04</td>
<td>14.53±0.04</td>
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<tr>
<td>1390H1</td>
<td>1390</td>
<td>1</td>
<td>83.84±0.05</td>
<td>5.58±0.03</td>
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<tr>
<td>1390H2</td>
<td>1390</td>
<td>2</td>
<td>87.92±0.10</td>
<td>8.92±0.05</td>
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<tr>
<td>1390H3</td>
<td>1390</td>
<td>3</td>
<td>95.83±0.08</td>
<td>14.93±0.06</td>
</tr>
<tr>
<td>1390H4</td>
<td>1390</td>
<td>4</td>
<td>93.42±0.05</td>
<td>14.75±0.08</td>
</tr>
</tbody>
</table>

The injection moulded green samples were first treated with solvent debinding, using trichloroethylene at 40°C for 10 h, and then thermally debound at ~600°C–900°C for 2 h under flowing hydrogen in a tube furnace. It was found that debinding at 900°C was the optimum temperature to give the samples sufficient strength to be transferred to a vacuum furnace for final sintering. A low debinding/presintering temperature (900°C) also ensures low oxidation content in the samples.

It was established, as can be seen in Table 1, that, when sintered in vacuum at 1390°C for 3 h, the relative density of 95.83% can be achieved for the NiAl-alloy samples, which is comparable to the relative densities of 94.5–97.3% for samples obtained by injection moulding in similar studies. The authors reported that a shrinkage of ~14.93% occurred in the sintered sample compared to the green sample.

XRD patterns in the sintered microstructures were found to be composed of the NiAl phase and the Cr(Mo) phase with maximum density values as shown in Table 1. When sintered at 1390°C and holding time of 3 h, the yield strength increases to 1133 MPa and the ultimate compressive strength increases to 3225.2 MPa (Fig. 1). The values for ultimate compressive strength for the MIM NiAl-based alloy obtained in this research were found to be more than 130% higher than that of other NiAl-based alloys processed by pressureless sintering. Meanwhile, the corresponding elongation level reaches 25.5%. The high yield strength of the NiAl-alloy is said to be significantly increased because of the high strength of the Cr(Mo) phase. The authors concluded that, in addition to the good properties obtained by the MIM process for the NiAl-alloys, MIM also has the advantage of being able to produce components to net- or near-net shapes, which would be difficult and costly using conventional forming and machining processes.

Fig. 1 The compressive stress–strain curves and properties of the NiAl-based alloys sintered at 1390°C for different times. (From paper: ‘Study of NiAl-based alloy parts produced by metal injection moulding’, by Bao Wang et al. Powder Metallurgy, Vol. 65, No. 1, 2022, 52-60)
OUR BUSINESS is a network of companies with 25+ years in the isostatic pressing industry. We design and manufacture research and full scale production units. In addition, we run our own units in service of the production and research hot isostatic pressing markets.
Boron carbide \((B_4C)\) is known for its high hardness (> 3200 Vickers), high melting point (2450°C), and low density (2.52 g/cm\(^3\)), and is widely used in abrasive applications such as sand-blasting nozzles, grinding and polishing media, water jet cutter nozzles, and wear-resistant coatings. The high hardness of \(B_4C\) also makes it an ideal material for lightweight armour applications and, because of the neutron absorption cross-section of boron, \(B_4C\) also finds applications in nuclear reactors. There are, however, a number of challenges associated with producing \(B_4C\), especially when complex shapes or shapes with internal structures are required, or when pore-free, fully dense bodies need to be produced in order to achieve the desired beneficial properties. Sintering \(B_4C\) is challenging due to densification mechanisms, such as grain boundary and bulk diffusion, becoming effective only at temperatures > 2200°C, and to produce commercially viable \(B_4C\) components with complex geometries, production methods other than pressure-assisted sintering (e.g. hot pressing) must be used.

Injection moulding using a conventional ceramic/polymer feedstock is, therefore, an attractive alternative because of its ability to produce ceramic near-net shape parts quickly at low cost. However, this approach requires multiple heating and cooling cycles, along with lengthy polymer debinding cycles prior to sintering. Even when the organic binder materials have been removed during debinding, the resulting sintered parts can still contain some porosity. A new approach, which overcomes the limitations of conventional ceramic injection moulding by using water-based ceramic suspensions, has been developed at the School of Materials Engineering, Purdue University, West Lafayette, Indiana, USA, and a paper outlining the results of the research has been published in *Ceramics International*, Vol. 45, January 2022, 11588–11596.

The authors (E A Weaver et al) stated that a number of different highly loaded (> 50 vol.%) aqueous \(B_4C\) suspensions were investigated. These suspensions allow flow into the polymer resin moulds at room temperature and retain their shape after removal of the stress. Parts made this way are subsequently dried and demoulded. Less than 5 vol.% polymer binder is added, greatly simplifying the debinding process. Three sintering aids: \(Al, Al_2O_3,\) and \(Y_2O_3\) were added to the aqueous \(B_4C\) suspensions, due to their ability to produce \(B_4C\) components of high density while only requiring small amounts of additives. Table 1 shows the ten different \(B_4C\)-based compositions investigated by the authors.

Previous work done by the research team on \(B_4C\) suspensions found that polyethylenimine (PEI) acts as an excellent electrostatic dispersant for \(B_4C\) powders. Hydrochloric acid (HCl) was used to modify the pH of the suspensions for increased dispersion. The amounts of PEI and HCl used in this study were both 3.57 vol.%. Suspensions were prepared by mixing the dispersant and HCl with reverse osmosis (RO) water in a dual-centrifugal speed mixer. \(B_4C\) and the sintering aid were then added in small (15–20 g) increments. Mixing increments were performed for 1 min at 800 rpm followed by 1 min at 1200 rpm, with the total mixing time taking less than 30 min. After mixing, five 12.5 mm WC-Co milling media were added and the suspension was ball milled for approximately 24 h. The use of the WC-Co milling media resulted in WC amounts of up to 10 wt% in the \(B_4C\) suspension, which was found to react with boron atoms in \(B_4C\) to form \(W_3B_2\), which in turn aids densification during sintering.

### Table 1 Compositions of \(B_4C\) suspensions used in injection moulding experiments. (From paper: ‘Mechanical properties of room-temperature injection moulded, pressurelessly sintered boron carbide’, by E A Weaver, B J Stegman, R W Trice, J P Youngblood. *Ceramics International*, Vol. 48, January 2022, 11588–11596)

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Sintering aid</th>
<th>Sintering aid amount (wt. %)</th>
<th>WC-Co content (wt. %)</th>
<th>Dispersant content (vol. %)</th>
<th>HCl content (vol. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_4C)</td>
<td>N/A</td>
<td>5</td>
<td>3.57</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>5 wt.% (Y_2O_3)</td>
<td>(Y_2O_3)</td>
<td>5</td>
<td>3.57</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>10 wt.% (Y_2O_3)</td>
<td>(Y_2O_3)</td>
<td>10</td>
<td>5</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>15 wt.% (Y_2O_3)</td>
<td>(Y_2O_3)</td>
<td>15</td>
<td>5</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>1 wt.% Al</td>
<td>Al</td>
<td>1</td>
<td>3.57</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>2 wt.% Al</td>
<td>Al</td>
<td>2</td>
<td>3.57</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>3 wt.% Al</td>
<td>Al</td>
<td>3</td>
<td>3.57</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>1.87 wt.% (Al_2O_3)</td>
<td>(Al_2O_3)</td>
<td>1.87</td>
<td>5</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>3.71 wt.% (Al_2O_3)</td>
<td>(Al_2O_3)</td>
<td>3.71</td>
<td>5</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>5.52 wt.% (Al_2O_3)</td>
<td>(Al_2O_3)</td>
<td>5.52</td>
<td>5</td>
<td>3.57</td>
<td>3.57</td>
</tr>
</tbody>
</table>
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The No.1 MIM powder manufacturer in China

中国最大MIM粉末厂家，始于1996

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生产工艺：水气联合和气雾化

MIM powder: 304L, 316L, 17-4PH and F75

主要产品: 304L, 316L, 17-4PH 和 F75等

Main application industry: MIM, 3D printing etc

主要应用领域: MIM,3D打印等

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Mobile: +86 13290511818
Web: www.liudemimpowder.com
Following successful injection moulding, demoulding and drying without any cracking or defects, the moulded B₄C samples underwent binder burnout to remove all organic compounds. This was done in a tube furnace with flowing Argon [Ar] at a heating rate of 1°C/min to 500°C where they were held for 25 h. Pressureless sintering was carried out in a graphite crucible with a flowing Ar atmosphere. A heating rate of 25°C/min to 2075°C, followed by a 4 h hold, was used to densify the parts.

As can be seen in Table 2, the average relative sintered density of boron carbide with no sintering aid was 92.6%, which is higher than is often reported in literature. This can be attributed to the presence of WC-Co contamination from attrition milling of the B₄C suspension, as mentioned above. The densities of B₄C suspensions containing the sintering aids Y₂O₃, Al, or Al₂O₃ were statistically improved even further. Additions of 10 wt.% Y₂O₃ was the most effective sintering aid overall, with an average relative density of 97.7%. The 1 wt.% Al and 1.87 wt.% Al₂O₃ compositions also achieved high relative densities of 96.9% and 95.7%, respectively.

The high sintered densities achieved in the B₄C samples resulted in high hardness values (up to 3200 Vickers). The flexural strength of the samples was said to be limited by grain pull-out during polishing of the tensile surface; the strength was correlated to the maximum grain pull-out flaw measured at the intersection of the tensile surface and the fracture surface (R² > 0.98). The grain pull-out was said to worsen as grain size increased, which indicated that modifying sintering parameters to control grain growth could mitigate this issue in future work.

The authors concluded that room-temperature injection moulding, in conjunction with pressureless sintering aids such as Y₂O₃, could expand the use of B₄C due to its ability to produce near net shapes of high density and favourable mechanical properties.

https://www.journals.elsevier.com/ceramics-international

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Maximum sintered relative density (%)</th>
<th>Average sintered relative density (%)</th>
<th>Vickers Hardness (HV)</th>
<th>Average four-point flexural strength (MPa)</th>
<th>Characteristic strength (MPa)</th>
<th>90% Confidence bounds</th>
<th>Weibull Modulus</th>
<th>90% Confidence Bounds</th>
<th>Average grain size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B₄C</td>
<td>92.6</td>
<td>90.0 ± 0.5</td>
<td>2470 ± 47</td>
<td>295.3 ±15.2</td>
<td>322</td>
<td>292–356</td>
<td>8.6</td>
<td>3.9–12.1</td>
<td>2.9 ±0.1</td>
</tr>
<tr>
<td>5 wt.% Y₂O₃</td>
<td>94.8</td>
<td>92.7 ± 0.5</td>
<td>2994 ± 41</td>
<td>176.6 ± 5.7</td>
<td>184</td>
<td>170–200</td>
<td>9.5</td>
<td>4.7–13.2</td>
<td>32.4±1.1</td>
</tr>
<tr>
<td>10 wt.% Y₂O₃</td>
<td>97.7</td>
<td>95.5 ± 0.5</td>
<td>3208 ± 53</td>
<td>212.4 ± 3.6</td>
<td>218</td>
<td>209–227</td>
<td>18.4</td>
<td>9.7–25.2</td>
<td>41.3±0.7</td>
</tr>
<tr>
<td>15 wt.% Y₂O₃</td>
<td>95.6</td>
<td>94.8 ± 0.2</td>
<td>3148 ± 66</td>
<td>150.0 ± 2.3</td>
<td>153</td>
<td>148–158</td>
<td>20.4</td>
<td>10.8–28.0</td>
<td>58.7±1.3</td>
</tr>
<tr>
<td>1 wt.% Al</td>
<td>96.9</td>
<td>93.5 ± 0.4</td>
<td>2911 ± 38</td>
<td>274.3 ± 7.0</td>
<td>285</td>
<td>268–303</td>
<td>11.5</td>
<td>6.1–15.8</td>
<td>10.8±1.5</td>
</tr>
<tr>
<td>2 wt.% Al</td>
<td>95.1</td>
<td>93.9 ± 0.4</td>
<td>3000 ± 39</td>
<td>261.3 ± 13.0</td>
<td>290</td>
<td>269–313</td>
<td>11.3</td>
<td>5.2–15.9</td>
<td>13.2±1.3</td>
</tr>
<tr>
<td>3 wt.% Al</td>
<td>95.1</td>
<td>94.2 ± 0.2</td>
<td>3076 ± 21</td>
<td>265.5 ± 8.9</td>
<td>276</td>
<td>251–306</td>
<td>9.9</td>
<td>4.1–14.2</td>
<td>10.6±1.6</td>
</tr>
<tr>
<td>1.87 wt.% Al₂O₃</td>
<td>95.7</td>
<td>92.9 ± 0.8</td>
<td>2954 ± 32</td>
<td>271.3 ± 19.0</td>
<td>304</td>
<td>264–352</td>
<td>5.3</td>
<td>2.6–7.4</td>
<td>9.5±2.3</td>
</tr>
<tr>
<td>3.71 wt.% Al₂O₃</td>
<td>95.2</td>
<td>94.7 ± 0.1</td>
<td>3004 ± 33</td>
<td>254.9 ± 10.2</td>
<td>267</td>
<td>241–298</td>
<td>7.9</td>
<td>3.7–11.3</td>
<td>10.4±3.8</td>
</tr>
<tr>
<td>5.52 wt.% Al₂O₃</td>
<td>94.1</td>
<td>93.4 ± 0.2</td>
<td>3116 ± 28</td>
<td>265.1 ± 10.0</td>
<td>279</td>
<td>256–306</td>
<td>7.9</td>
<td>4.2–10.8</td>
<td>8.1±1.6</td>
</tr>
</tbody>
</table>

Table 2 Physical and mechanical properties of sintered B₄C bars of each composition used in this study. (From paper: ‘Mechanical properties of room-temperature injection moulded, pressurelessly sintered boron carbide’, by E A Weaver, B J Stegman, R W Trice, J P Youngblood. Ceramics International, Vol. 48, January 2022, 11588–11596)
CHINA’S LEADING SUPPLIER OF MIM POWDERS
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The company provides various types of structural material powders, magnetic material powders, and other alloy powders in a variety of particle sizes and tap density based on the demands of the customers. The product line includes 316L, 304L, 17-4PH, 4J29, F75, HK30, 420W, 440C, Fe2Ni, 4140, and FeSi. The customers have received the products with high acclaim.

<table>
<thead>
<tr>
<th>Item</th>
<th>T.D(g/cm³)</th>
<th>S.S.A(m²/g)</th>
<th>S.D(g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>316L</td>
<td>4.8</td>
<td>0.34</td>
<td>7.9</td>
</tr>
<tr>
<td>17-4PH</td>
<td>4.7</td>
<td>0.34</td>
<td>7.7</td>
</tr>
<tr>
<td>304L</td>
<td>4.8</td>
<td>0.34</td>
<td>7.8</td>
</tr>
<tr>
<td>HK30</td>
<td>4.7</td>
<td>0.34</td>
<td>7.7</td>
</tr>
<tr>
<td>4J29</td>
<td>4.9</td>
<td>0.34</td>
<td>7.95</td>
</tr>
<tr>
<td>F75</td>
<td>5.0</td>
<td>0.34</td>
<td>8.1</td>
</tr>
</tbody>
</table>
Correlating MIM feedstock mouldability with melt viscosity and dry powder rheology

The influence of powder characteristics on the mouldability of feedstocks for Metal Injection Moulding is relatively well understood, although special attention still has to be paid to control the feedstock fluidity during the injection stage in order to avoid defects such as flashes, sinks or voids, which can impair the green part integrity. This requires the correlation of feedstock mouldability performances with melt viscosity and dry powder rheology, which remains difficult to ascertain other than by real-scale injections. Research at École de technologie supérieure, Montréal, Canada, has recently focused on developing indirect techniques such as the use of powder rheometers to characterise the dry rheology of typical MIM powders and to better understand its correlation with the feedstock melt rheology and mouldability. The results of the research have been published in a paper by D Langlais, V Demers and V Brailovski in the journal Powder Technology, Vol. 396, 2022, 13-26.

The authors reported in their paper on the influence of powder characteristics on dry powder rheology, powder-binder feedstock melt viscosity and MIM feedstock mouldability using four typical powders belonging to the commercial 17–4 PH stainless steel class (Fig. 1 and Table 1). These powders, one gas atomised and three water atomised, were characterised using an FT4 powder rheometer under three dry testing conditions (free surface, aerated, and packed) and applying five testing protocols (dynamic, aeration, compressibility, permeability, and shear). Each type of powder was then premixed using the same wax-based binder system and an identical solid loading to formulate four MIM feedstocks.

The solid loading in the feedstocks was set at 60 vol.% of powder and the binder was formulated from 30 vol.% of paraffin wax, 7 vol.% of...
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[caption image]

Fig. 2 (a) Viscosity profile (90°C), and (b) spiral flow distance (SFD) for feedstocks formulated with powders G-12, W-10, W-7, and W-3. [From paper: ‘Rheology of dry powders and metal injection molding feedstocks formulated on their base’, by D Langlais, et al. Published in Powder Technology, 396, 2022, 13-26]

The authors stated that understanding the full extent of these interactions is still very much an actual research topic in the field of MIM.

Following mixing, the four feedstocks were subjected to rheological testing to obtain their melt viscosities as a function of the shear rate. This procedure generated fifteen rheology metrics: fourteen dry powder metrics obtained under different stress conditions and one melt viscosity metric. All the metrics were then related to the feedstock mouldability, which was quantified using real-scale injections into a spiral mould cavity. The results for the measured spiral flow distance (SFD), also known as the length, are shown in Fig. 2 (b), along with feedstock melt viscosity profiles obtained at 90°C, shown in Fig. 2(a).

The authors stated that the obtained viscosity profiles can be divided into three zones, as can be seen in Fig. 2(a). At low shear rates, Zone #1 is characterised by a plateau-like behaviour showing a slight decrease followed by a slight increase in viscosity for the powders produced by water atomisation (W-10, W-7, & W-3), but not for powder G-12 produced by gas atomisation. Although this phenomenon has been observed by several research teams cited by the authors, it remains poorly understood. To date, the well-accepted explanation states the difficulty in forming particle layers, leading to particles sliding over each other and thus producing an overall increase in viscosity, which was visible in this work only for powders exhibiting more surface texture and less sphericity. As the shear rate increases, a restructuring in the mixture caused by a progressive alignment of binder molecule chains and powder particles with the flow, leads to a clear shear thinning behaviour (depicted by Zone #2 in Fig. 2(a) and a tendency to exhibit a Newtonian-like behaviour observed in Zone #3 for all feedstocks.

Similar to the conclusions drawn with the melt viscosity data, the authors reported that spiral flow distance was clearly influenced by powder characteristics, with the highest and lowest values obtained for powders G-12 and W-3, respectively. As anticipated from the viscosity profiles, powders W-10 and W-7 exhibited similar moulding behaviours, since no significant differences in their average SFD were observed (p-value = 11%, t-test).

The authors concluded the results of their study as follows:

- An increase in powder size or sphericity results in an increase in mouldability. The injected length was clearly affected by the size of powders (W-10 vs W-3) and their shape (G-12 vs W-10). However, no significant impact on mouldability was recorded for feedstocks formulated with similar powder sizes (W-10 vs W-7).

- The inversely proportional relationship between mouldability and melt feedstock viscosity was confirmed by a strong correlation. Thus, the melt viscosity determination provides a less complex approach than the real-scale injection in evaluating the impact of powder characteristics on feedstock mouldability.

- Dry powder rheology metrics NBFE and CBD also demonstrated a strong correlation with feedstock mouldability. As FT4 dry powder rheology measurements require fewer resources, this technique becomes an interesting and reliable alternative to real-scale injections - or even to melt viscosity measurement - in predicting the influence of powder characteristics on feedstock mouldability.

Compared to real-scale injections, these simplified tests (especially dry powder rheology) could, therefore, be considered as rapid and reliable approaches to assessing the impact of powder characteristics on the mouldability of powder-binder feedstocks used in Metal Injection Moulding.

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Where ideas take shape.
Frank Petzoldt on the past, present and future of Metal Injection Moulding technology

There can be few people in Europe’s MIM industry, if not further afield, who are unaware of Prof Dr Frank Petzoldt’s contribution to the development and promotion of the technology over more than three decades. Following his recent retirement from the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Bremen, Germany, Dr Petzoldt spoke with Dr Georg Schlieper about the past, present and future of MIM technology and shares his insight into the industry in both Europe and worldwide.

The story of Frank Petzoldt’s career goes hand in hand with the story of the Fraunhofer Institute for Manufacturing Technology and Advanced Materials, commonly known as Fraunhofer IFAM. Born in 1956, Petzoldt joined Fraunhofer IFAM in 1984 as a Project Engineer at a time when the institute only employed about seventy staff. He remained there until his retirement from the position of Deputy Director a few months ago, leaving behind a thoroughly modern institute which employs around 700 people at a number of locations in Germany.

The Fraunhofer IFAM branch in Dresden, which today has a similar status to the original institute in Bremen, is the most notable of the satellite locations, created following the reunification of Germany in 1990. Further locations were added in the following years and, like all institutes of the Fraunhofer Society, Fraunhofer IFAM focuses on industry-related contract research.

Powder technology has been a focus of research at Fraunhofer IFAM for many decades. One of Petzoldt’s first areas of activity when joining the institute was the sintering of tungsten heavy alloys. Soon after, he was given the opportunity to do his doctorate, with the topic of his dissertation being the production of amorphous metals by mechanical alloying. Early in the 1990s he was given more responsibility, initially being promoted to Group Leader and then, in 1993, appointed as head of the Powder Technology department. In 1999, he was appointed Deputy Director of the institute, a position that gave him a controlling role and, with it, the opportunity to exert influence on strategic decision making.

For more than three decades, both Petzoldt’s career and the work at Fraunhofer IFAM have followed...
the rise of the Metal Injection Moulding industry. “It is very unusual for one technology, such as MIM, to be covered at a Fraunhofer Institute over such a long period. However, this meant that many consecutive research contracts from industry partners could be secured over this extended period of time as new materials and applications were commercialised,” stated Petzoldt.

“The MIM industry in Europe has enjoyed continuous growth in recent decades. Even the financial crisis of 2008 did not lead to a permanent slump in demand for MIM products. This positive development enabled the industry to invest continuously in research. Even today, in the pandemic, I perceive a positive mood in the MIM industry.”

Milestones for the MIM industry and some of the companies which enabled growth

BASF and the binder revolution
When considering milestones in the industrialisation of MIM technology, Petzoldt called to mind BASF’s introduction of its binder system based on polyoxymethylene (POM) at the beginning of the 1990s as a key turning point. “Until then, wax-based binder systems were mainly used, which required extremely lengthy thermal debinding processes,” he stated.

“With BASF’s Catamold system, which is debound in a catalytic process, debinding times were drastically reduced. At the same time, the dimensional stability of the parts produced was outstanding. BASF thus made it easier for many companies to get started with MIM production and helped to ensure that MIM was perceived as a mature and safe technology.”

BASF’s Catamold business model focused on supplying a core number of materials that are most frequently used in mass production, enabling it to produce feedstock more efficiently in larger batches. “From the beginning of the Catamold era, MIM manufacturers who wanted an extended range of materials and special materials had to use different binder technology. Of course, after the expiry of BASF’s patent, other feedstock suppliers developed their own POM-based binder formulations, thereby expanding the range of available materials.”

However, Petzoldt stressed that there are many large and very successful companies in the MIM industry that have worked with their own binder formulations from the beginning and continue to do so. The diversified market for MIM binder technologies that exists today has resulted in many innovations, most notable of which, stated Petzoldt, being the introduction of water-soluble binder components.

“As a result of this type of innovation, the environmental impact of the MIM process has been significantly reduced.”

Tailoring injection moulding machines for MIM
“The name Arburg cannot be missed when one reflects on the growth of MIM. The company has been a key figure in the adaptation of plastic injection moulding technology to MIM and process-specific developments in the MIM sector,” stated Petzoldt. “Arburg was the first manufacturer of injection moulding machines to recognise the potential of MIM and set up an Application Centre specifically for MIM and CIM products. Here, the company’s technicians studied the MIM process in every detail and optimised their injection moulding machines accordingly.”

“Based on their expertise, they were able to give valuable advice to their global customers when problems arose,” he continued. “Other manufacturers of injection moulding machines do not have this in-depth experience with the production of MIM components. As a result, Arburg has gained a clear competitive advantage, worldwide.”

Furnaces makers enabled stable high-volume debinding and sintering
“Following the arrival of Catamold, the competitive mass production of MIM parts was enabled by the introduction of the continuous debinding and sintering furnace. First and foremost in this development was Cremer Thermoprozessanlagen GmbH, which produced the first walking-beam furnace for MIM parts in 1992, a model which was later exported all over the world under the name MIM-Master”.

Another furnace specialist which has driven the rise of MIM technology is the US company Elnik Systems, which has dominated the market for MIM batch vacuum furnaces. “Today, Elnik’s solutions for debinding and sintering are used for both MIM and numerous ‘sinter-based’ process variants driven by the growth of Additive Manufacturing,” commented Petzoldt.

“The diversified market for MIM binder technologies that exists today has resulted in many innovations, most notable of which, stated Petzoldt, being the introduction of water-soluble binder components.”
Automation increases efficiency and quality

For Petzoldt, the widespread use of automation in MIM manufacturing is one of the outstanding milestones on the road to the industrialisation of MIM. “In the early days, MIM production was still largely based on manual work. Burrs and sprues on green parts were removed by hand, then the parts were placed on trays for debinding, possibly repacked again for sintering and checked by hand after sintering,” he explained.

“This has fundamentally changed all over the world. What used to be done by hand is now being carried out by pick-and-place systems and robots. As a result, not only an increase in the efficiency of production has been achieved, but also significant quality improvements and a drastic reduction in reject rates.”

Improvements to the machines, giving higher accuracy and better control, have also contributed to significant advances in product quality, he added.

Research as a driver for new applications and process evolution

In-house research leads to commercial success

In addition to research contracts from industry, research is also carried out at Fraunhofer IFAM based on its own initiatives. As an example, Petzoldt mentioned the application of two-component injection moulding in MIM technology. Today, Germany’s Schunk Sintermetalltechnik GmbH manufactures such two material, or two-colour, parts in high volume. In the example shown in Fig. 2, a low-alloy steel is combined with a wear resistant alloy for an automotive application. Another application developed at Fraunhofer IFAM is the suture anchor shown in Fig. 3. This part consists of the composite material iron-tricalcium phosphate (Fe-TCP) and was made by MIM at Fraunhofer IFAM. This medical application uses material that is degradable in the body.

The evolution of process simulation

Process simulation for MIM is, states Petzoldt, an essential development that is still being evolved. Whilst major MIM manufacturers are now routinely using computer simulation, the technology is also accessible to many smaller firms.

“Mould filling behaviour during injection moulding can now be predicted very well, avoiding many of the delays that are associated with tool modifications. Sigmasoft, based in Aachen, Germany, is a market leader here. The next steps are the development of software capable of accurately predicting machine parameters such as pressure and temperature during injection moulding, enabling the development of defect-free components in the shortest possible time,” explained Petzoldt.

In addition to the simulation of injection moulding, which is already very advanced, work has been underway for about thirty years on the simulation of sintering. “Interest...
in this has without doubt been given a new boost by the rise of sinter-based AM. Previous work focused on the development of models that describe the processes in the most accurate way possible. In the meantime, however, there are also new approaches based on process data, with the required data determined by experiments.”

Petzoldt’s vision of the future in the longer term sees the use of quantum computers in computer simulation. “Quantum computers no longer calculate only with zero and one, but with probabilities in a space. This results in many possible solutions, in a similar way to the human brain. The different solutions are evaluated and a solution is selected that seems most likely. Quantum computers will be able to process the huge amounts of data generated in a manufacturing plant, intelligently correlate them and derive from them how safely the process runs.”

In cooperation with partner companies, Fraunhofer IFAM has already gained experience with so-called neural networks. In conjunction with the development of quantum computing, Petzoldt expects a further quantum leap in the technical development of MIM manufacturing.

Frank Petzoldt on MIM

Research at Fraunhofer IFAM is by no means limited to powder technology, extending, for example, to the development of electrical energy and hydrogen storage systems, fuel cells, and lightweight construction. When it comes to electromobility, the Powder Technology team supports the automotive sector by participating in the development of, amongst other applications, hard and soft magnetic components for electric drives.

Beyond the automotive industry, Petzoldt cites the aerospace industry as holding many opportunities for MIM. “New market segments are constantly being opened up; for example, recently, some successful components for the aerospace industry have been developed in Europe. I see the most dynamic growth markets for the MIM industry being for applications in aerospace and medical technologies.”

Petzoldt added that one crucial future research area that will open up many new areas of application is a thorough investigation of the influence of residual porosity in MIM materials on their fatigue strength.

Roadmaps for sustainability and digitisation

The topic of sustainability is also currently of high interest throughout industry. “MIM’s customers are increasingly making sure that their suppliers manufacture parts sustainably,” Petzoldt said. “The question of whether MIM is a sustainable manufacturing process must be answered by the MIM industry itself.”

Together with the European MIM industry, Petzoldt has developed two roadmaps, one on sustainability and a second one on digitisation. “The roadmap for the sustainability of the MIM industry identifies at which points in the MIM process progress towards sustainability is possible,” he explained, “be it in powder production from recycled material, in energy savings in the sintering process, in reducing reworking operations, etc. I am convinced that sustainability
improvements will be of great importance for research during this decade.”

Thoughts on MIM in Asia and North America

The rapid development of the MIM industry in Asia, especially in China and India, has left a lasting impression on Petzoldt, as it has for most observers. He reflected on a visit to a Chinese company that manufactures MIM parts in such large quantities that a new injection mould was made every week - simply because the old mould was worn out. “I found the dependence of this company on a few components frightening, because the company would very quickly get into economic difficulties if some of these products were to disappear.” His hosts in China were acutely aware of this problem, expressing a desire to diversify into markets other than consumer electronics, such as the automotive sector.

“In addition, I noticed that the company had invested very heavily in machinery and equipment even before there were orders for products that could be manufactured with these systems,” he recalled. “In Europe, such an approach would be unimaginable. This seems to be a fundamental difference in the corporate philosophy between Asia and Europe.”

When talking about the MIM industry in Asia, Petzoldt stated that one cannot ignore Indo-MIM. “This company plays a special role worldwide, as it has production facilities in both India and North America. It alone has revenues comparable to those of the entire German MIM industry combined, making it one of the most important global players by far. The company is active globally and in all MIM markets, offers an extraordinary variety of materials and reacts extremely flexibly to customer requirements,” commented Petzoldt.

The North American MIM industry, he said, appears relatively static. The relevant markets – mainly firearms, automotive and medical technology – seem to be quite stable. “I believe that there is a research culture in Europe that is more firmly established than in North America or Asia,” he explained. “It would be good to see more funds invested in research and development there.”

Marketing MIM: insight into the MIM-Expertenkreis

For nearly thirty years, there has been a grouping of MIM industry leaders in German-speaking countries which promotes the dissemination and further development of MIM technology. Among the more than thirty-five members of the ‘MIM-Expertenkreis’ (expert working group) are manufacturers of MIM parts, suppliers of raw materials and production equipment, as well as research institutes.
MIM-Expertenkreis members meet twice a year to coordinate activities. In recent years, the group has organised webinars to raise awareness of MIM technology as well as to tackle the issue of sustainability at a European level. “The trust and cooperation shown by these companies, many of which are also competitors, is probably something extraordinary and unique,” Petzoldt noted.

“Networking has proven itself over many years, as everyone pursues the same goal: namely, to advance MIM technology. Efforts are also being made to better connect the MIM industry worldwide through the support of informal initiatives such as the popular MIM parties at recent PM World Congresses.”

There is still the prevailing impression that young design engineers know far too little about the possibilities offered by MIM. “For thirty years, we’ve been trying to communicate the knowledge about MIM to end-users,” Petzoldt said. “Nevertheless, I have repeatedly noticed that many designers still have a great deal of uncertainty about the reliability of MIM parts.”

To try and address this, a novel approach was taken by the group. “We decided to create ten briefcases with 26 sample parts each, which are loaned to university teachers so that they can show their students real-world sample parts, supported by a set of explanatory notes. In addition, the promotion of MIM technology at trade fairs such as the Hannover Messe or Formnext also helps to make the process better known to students and designers. However, such actions are associated with a lot of effort and unfortunately only work in the long term,” stated Petzoldt.

On a positive note, Petzoldt commented that it is not only Fraunhofer IFAM which is active in the research, product development and promotion of MIM technology. “Work is ongoing at various universities in Europe, where there is a focus on both MIM research and education, and this has introduced MIM to many students. Good example of this are in Spain, notably at universities in Madrid and Ciudad Real.”

**Additive Manufacturing as a catalyst for MIM technology?**

In Petzoldt’s view, the current high levels of interest surrounding Additive Manufacturing, especially sinter-based processes, may contribute to a greater acceptance of MIM technology in the market. “Many European MIM manufacturers have recognised that AM is a useful addition to MIM and are building up their own production capacities,” he stated.

Fraunhofer IFAM began researching metal AM in the early 1990s and one of the first EOS machines for Laser Beam Powder Bed Fusion (PBF-LB) was installed at Fraunhofer IFAM in Bremen. This
was soon followed by a system for metal Binder Jetting (BJT). In the intervening years, however, before the resurgence in interest of the last eight to ten years, activities around these processes decreased, Fraunhofer IFAM’s work was stopped, and the machines were decommissioned. The knowledge that was gained about AM, however, remained with Fraunhofer IFAM’s engineers. Re-entering Additive Manufacturing was therefore easier for Fraunhofer IFAM than for many others, thanks to the early experience with the technology. Today, Fraunhofer IFAM works with several additive processes, with Petzoldt considering BJT to be the most promising variant of sinter-based AM processes.

“For companies that manufacture MIM parts, a major advantage is that Binder Jetting can easily be integrated into their production. The printing process is at least an order of magnitude faster and the process is therefore much more economical than the laser-based processes,” he explained. Petzoldt is certain that, with BJT, quantities of several thousand AM parts are economically feasible. Thus, the process seamlessly closes the gap to the tool-bound MIM process in terms of production quantities.

However, Petzoldt also warns that disappointment threatens if very high expectations are set for AM too quickly. “Often, applications based on these new technologies cannot be immediately manufactured to the necessary quality, be it in terms of dimensional accuracy, surface quality or strength. A lot of development work is still needed for the technology to become robust.”

“I fear that if a customer finds that an additively manufactured component made by a process such as Binder Jetting does not meet all requirements, they could conclude that MIM technology is also unreliable. One should always take into account that the additive processes are still very young and that MIM technology has been on the market for far longer and is extremely well established.”

**Conclusion**

Frank Petzoldt leaves a very different organisation to the one he joined nearly forty years ago. His departure, however, does not signal a slowing down of the institute’s activities. Fraunhofer IFAM’s research on MIM technology will be continued by his successor, Sebastian Hein, who also takes over the chairmanship of the MIM-Expertenkreis.

The MIM industry has changed dramatically over the period that Petzoldt has been at Fraunhofer IFAM, and without doubt it is a technology that has had a major impact on industries such as consumer electronics, resulting in the rapid rise of China’s MIM sector, as well as the medical device industry, defence production and much more besides. The question remains, however, as to whether MIM has reached, or will, reach its full potential in more general industries that consume high volumes of small, complex components.

As Petzoldt stressed in this interview, MIM remains a technology with an awareness challenge, and far more needs to be done to make potential users aware of its capabilities and its green credentials. With this also comes a need to continue to overcome the industry’s historic secrecy and bring a greater level of transparency to the industry for the benefit of those in it and those looking to use it.

“The collection of economic data in the European PM industry, for example, is very difficult, and the data from MIM part producers is no exception. Although some limited data is collected every year, its reliability is low. Powder manufacturers and feedstock suppliers could also provide the most reliable information about powder and feedstock consumption, but many of them don’t disclose their sales data.”

Some good news? Whilst Petzoldt is stepping away from his role at Fraunhofer IFAM, he will not be stepping away from the technologies that he has worked on for so long. As a freelance technology and management consultant, he will continue to be an advocate for MIM and sinter-based AM technologies and work to overcome some of the challenges that remain in the way of the greater adoption of these technologies.

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Saturation in metal Binder Jetting: Simple in principle, complicated in practice?

As metal Binder Jetting (BJT) transitions from a technology for the future to a technology for now – and one that is increasingly being installed at Metal Injection Moulding producers around the world – one of the basics of the process that we can no longer avoid getting to grips with is saturation. In this article, longtime metal Binder Jetting expert Dan Brunermer, from technology consultancy B-jetting LLC, explains saturation and how to measure it, considers voxels and DPI, and finally presents control options and how choices in controls affect saturation.

Saturation, for the uninitiated, is the primary driving variable used when executing the manufacturing step required to make ‘green’ parts in Binder Jetting (BJT). It is simple to understand in principle, but can be difficult to understand when reducing principle to practice. This article will introduce several concepts key to understanding Binder Jetting technology’s #1 variable, including:

- The absolute basic steps of BJT Additive Manufacturing
- What saturation is and some basic units of measure
- What voxels are and how they are defined
- Binder nozzle geometries and how they relate to voxels
- Control options and how choices in controls affect saturation options.

A Binder Jetting primer

BJT Additive Manufacturing is a fast-growing manufacturing technology that is finding increasing uses in the Metal Injection Moulding industry, from the production of low-quantity prototypes to high-volume products. Like all Additive Manufacturing, this is a layer-based AM process and parts are built up one layer at a time, in this case by binding layers of powder together in a build box. A complete process for creating a finished, dense part usually consists of manufacturing, curing, depowdering, and sintering. There are many articles explaining the workflow, so this article will focus on the manufacturing step.

Fig. 1 Dan Brunermer, from technology consultancy B-jetting LLC, has decades of experience in metal BJT technology and application development
Saturation defined

Let us get the easy part out of the way and start with the basic definition of saturation and its underlying assumptions. Of the latter, the most important is that the powder we are binding is made of whole granules and that these are insoluble in the binder being jetted as the glue. This is true for 99% of metal BJT, as the binder is not normally mixed into the powder, but it is not true for several other forms of BJT, nor when binding some agglomerates. This discussion will only lightly describe variable-sized drops, as they are an emerging laydown strategy.

Given a contained volume of powder \( V_c \) with dimensions \( X \times Y \times Z \), we can say the container is filled with solid granules and air. That is,

\[
V_c = X \times Y \times Z
\]

\[
V_c = V_{\text{powder}} + V_{\text{air}}
\]

We can introduce the term ‘Packing Rate’, \( PR \), to express the ratio of the measured powder density to the material’s solid density, and rewrite.

\[
V_c = PR \times V_c + (1 - PR)V_c
\]

\[
V_{\text{powder}} = PR \times V_c ; V_{\text{air}} = (1 - PR)V_c
\]

If we fill \( V_{\text{air}} \) with some volume of binder, \( V_{\text{air,bndr}} \), we can define saturation, \( S \).

\[
S = \frac{V_{\text{binder}}}{V_{\text{air}}} = \frac{V_{\text{binder}}}{(1 - PR)V_c} \text{ for any } V_c
\]

This bulk property of saturation is true all the way down to the base unit level: the Voxel – I love this word, I have to say. It means Volumetric Picture Element. This is the most accurate and descriptive word that has been coined in a long
time. It is one ‘dot’ in a picture, extruded through some thickness. It is perfect. In Fig. 3, you can see this principle at work. For the typical BJT machine, the volume is broken down into discrete, fractional pieces. These cubic shapes can be of any size, ratiometrically, and, in most cases, X ≠ Y ≠ Z.

One needs to be familiar with a few terms not common in manufacturing processes. A BJT machine is often rated by the unit DPI, or Dots Per Inch. BJT follows 2D printing technology and, since much of that is based on typographic printing, it continues to be based on the old system of units ‘points’ and ‘picas’. You will often (though not always) see multiples of 6, 12, and 72 DPI.

DPI and Droplet Spacing are inverts, typically converted from inches to microns. The equation is a simple one:

\[
\text{Print density in DPI} = \frac{25,400 \, \mu m / in}{d \, \mu m}
\]

where \( d \) is the distance between drops

\[
d \, \mu m = \frac{25,400 \, \mu m / in}{\text{Print Density in DPI}}
\]

where DPI is the rated build density

You might see ‘accuracy’ listed in a machine specification as a number, like 63.5 µm. Using the equation, we can see this spacing describes a 400 DPI process. This is invertible and any distance can be used as a basis for a DPI (that is, if you have 1.016mm between dots, you could call it 25 DPI).

With this as background, we can take any volume \( V \) and decompose it to a combination of voxels

\[
dV_{\text{voxel}} = dX \cdot dY \cdot dZ
\]

Where \( dX \) is the X spacing between drops, \( dY \) is the Y spacing between drops, and \( dZ \) is the Z spacing between drops. We can say that each voxel is additively manufactured with one droplet of binder with volume \( V_{\text{drop}} \). With these new variables, we can rewrite the fundamental saturation equation:

\[
S = \frac{V_{\text{binder}}}{V_{\text{air}}} = \frac{V_{\text{drop}}}{(1 - PR)dX \cdot dY \cdot dZ}
\]

It is easy enough to understand that \( dZ \) is the layer thickness and it is easy enough to imagine a way to measure the droplet’s volume. Where the confusion comes is understanding where \( dX \) and \( dY \) come from and how a machine computes them. To understand that, we need to understand real-world inkjet Binder Jetting modules.

Before I get too far in, though, it is important to understand two things:

**Fig 3. A binder laydown schematic illustrating the method of calculating saturation**
This is just algebra! This is not physics!

Since it is just algebra, the equations can be easily manipulated.

By ’not physics’, I mean that this math cannot be used for things like simulations or making predictions about the interactions between a fluid and a powder, even when the physical properties of everything are known. These simple equations do not account for the real wetting phenomenon of the process. It is a short-hand method for relating the Additive Manufacturing strategy.

It is also based on volumes, not mass. Measuring volume is notoriously less precise than measuring weights, but, in this case, the percentages would feel strange to control. Saturation as a relationship between the volume of binder and volume of air in the powder is easy to understand and envision. This is especially true when moving between powder types.

Over the years, I have found that saturation does not generally vary a great deal and it is usually between 50-75%. Also, it is as true when additively manufacturing light materials like silica with non-reactive binders as it is when additively manufacturing denser materials like tungsten alloys. Likewise, most powders do not seem to vary that much by packing rate either, with a normal range of 50-60% solid. There are outliers, like sands and more filamentary particles, but, by and large, this is common.

If someone used mass ratio as the primary relationship expressing binder deposition rates to the mass of the voxel, they might be misled into thinking they are consuming much more binder in one case than the other. And the ‘feel’ for the consumption would be backwards.

For example, silicon carbide has a normal density of 3.21 g/cm$^3$. If you had a 55% dense powder additively manufactured at a saturation rate of sixty percent and back-calculate with a binder density of 1.05 g/cm$^3$, you would be applying binder at the rate of 13.8% by mass.

But, if you were additively manufacturing tungsten carbide, with a density closer to 15.6 g/cm$^3$, the same rate would be 3.3% by mass. And paradoxically, if you increase saturation to 80%, the mass ratio would only increase to 4.2%. It would be easy to think, at first glance, that the tungsten carbide was consuming less binder, when, in fact, it is not. Using volume ratios allows consumption rates to be compared consistently across different powder types more easily for the user.

We often want to compute the pair $dX$ and $dY$, given a desired saturation, a specified layer thickness, and...
a known powder packing rate. Here is the secret: it is as simple as rewriting the equation and understanding the constraints on \( dX \) and \( dY \).

\[
dX \times dY = \frac{V_{\text{drop}}}{(1 - PR) \times S \times dZ}
\]

This is where it starts to get confusing. To the user/operator, the number pairs for \( dX \) and \( dY \) can seem to come from nowhere, but, in fact, they are driven by two things: the physical layout of the jetting module[s] and the complexity of the controls available. To illustrate this, consider the Polaris PQ-512/85AAA module from FujiFilm Dimatix, shown in Fig. 4.

Though they could be assigned either way, \( X \) is generally defined as the axis in line with the nozzles, while \( Y \) is defined as the spacing between the jetted lines. In this example, the native \( dX \) spacing would be 127 microns (200 DPI), but \( dY \) will require more explanation.

The first constraint a typical BJT machine will place on the calculations is that they all must involve ‘whole drops’ and ‘whole voxels’. For \( dX \), it means we can only divide the spacing by an integer (or multiply the DPI by an integer) to achieve a new \( dX \) spacing. Practically, this means you can additively manufacture with spacings of 127 µm, 63.5 µm, 42.33 µm, etc., but you cannot choose 50 µm exactly.

You will find that, with most piezo-driven binder nozzles, there is an interplay and relationship between jetting frequency, droplet volume, and droplet velocity. Because of this, most machines are designed to additively manufacture by jetting with a constant frequency while moving the head at a constant velocity.

**Fig. 5 The resultant spacing from the interplay of velocity and frequency, \( dY \), is the build velocity \( \times \) the jetting period**

“You will find that, with most piezo-driven binder nozzles, there is an interplay and relationship between jetting frequency, droplet volume, and droplet velocity. Because of this, most machines are designed to additively manufacture by jetting with a constant frequency while moving the head at a constant velocity.”

**Mechanically, the same integer divider rule still applies vis-à-vis drop spacing. This example is challenging, as the intra-row spacing and the row-to-row spacing are not evenly divisible. The former, at 1.016 mm, means it has a native \( Y \) resolution of 25 DPI. But the second row is spaced at 8 mm (3.175 DPI) and these do not mix. No single DPI can be used that will allow the head to be fired as a complete unit, while also perfectly aligning every drop.**

**As an aside, this highlights one of the difficulties designers face when implementing binder nozzle controllers. Though it is not entirely apparent, a 2D printing matrix like the one shown here can often be controlled by firing each line of piezos independently, or in groups. However, this approach would require as many pulse generators and data-paths as the designer wants line-level control. It is a true ‘value engineering’ question.**

For the sake of an example, let us specify a laydown of 200 DPI \( \times \) 200 DPI and accept that the saturation value would be correct. It means that there would be 62.992 DROPS between row 1 and row 3. So if nozzle one drops at position = 0, nozzle two, 63 drops later, will drop at 0.001 mm, with a persistent .001 mm error in absolute drop placement in every line. The error is non-cumulative, but it is ever-present. For our purposes, we shall ignore it, but; if this fine level of a control were required for an application, at least two generators would be needed.

On the flip-side, though, if the decision was made to control all four lines independently, the value for \( dY \) would be nearly free-settable within the bounds of saturation. That is because you could always come up with a combination of position tracking and timing offsets to achieve (nearly) perfect spacing.

All that said, for the purpose of this discussion, we shall say DPI\(_i\) must be DPI\(_{\text{int}}\)\(^j\) where \( i \) is the number of passes. For this module, we shall use DPI\(_{\text{int}}\)=200 DPI. DPI\(_i\) must be DPI\(_{\text{int}}\)\(^j\)
and DPI will further be constrained by the frequency/velocity relationship. For this module, we shall use $DPI_{yr} = 25DPI$. With everything defined, the control software now starts computing $dX$ and $dY$ pairs to find the best fit.

At this step, the control system is looking primarily at the aspect ratio of the drop placement and it is using exact $dY$ values instead of constrained ones. $dY$ will be adjusted in the final calculation, but what the software examines first is the voxel aspect ratio.

$$AR_{voxel} = \frac{dY}{dX}$$

A good BJT process will try to operate as close to 1 as possible. In the example shown in Table 1, the software should pick option two. With two passes selected, the software will now rectify the $dY$ value. In this case, the Binder Jetting could be done with either 500 DPI or 525 DPI, both of which are detailed in Table 2.

Obviously, 500 DPI is closer to 504 than 525, so the former would be chosen. And that is it. The real saturation would be 69.4% and the machine would configure itself to build with a speed of 254 mm/s and a jetting frequency of 5 kHz. The final process will have resolutions 400 DPI (X) x 500 DPI (Y) x 338.7 DPI (Z). That translates to a neatly stacked grid of voxels with size 63.5 x 50.8 x 75 µm.

Though this is a contrived example with somewhat invented numbers, this is how a Binder Jetting machine works. While saturation is just a number, and the actual physics involved with Additive Manufacturing are much more complex than this suggests, strict control of it has proven to be a reliable method of achieving your best results for over twenty years.

“One while saturation is just a number, and the actual physics involved with Additive Manufacturing are much more complex than this suggests, strict control of it has proven to be a reliable method of achieving your best results for over twenty years.”

Table 1 An example of the Binder Jetting process’ ideal operations

<table>
<thead>
<tr>
<th>DPI(X) at 1 Pass</th>
<th>200 (dpi)</th>
<th>DPI(Y) at 1 Line</th>
<th>25 (dpi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packing Rate</td>
<td>0.5236 (%/100 - packing rate)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume of Droplet</td>
<td>80 (pl - drop volume)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturation Desired</td>
<td>0.7 (%/100 - saturation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer Thickness Z (µm)</td>
<td>75 (µm - layer thickness)</td>
<td>338.6666667</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>5000 (Hz - frequency)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>If # of Passes is</th>
<th>1 then DPI is</th>
<th>2 then DPI is</th>
<th>3 then DPI is</th>
<th>4 then DPI is</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (µm)</td>
<td>127.00</td>
<td>63.50</td>
<td>400.00</td>
<td>600.00</td>
</tr>
<tr>
<td>Y (µm)</td>
<td>25.19</td>
<td>1008.51</td>
<td>504.25</td>
<td>336.17</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>5.04 = X/Y</td>
<td>1.26 = X/Y</td>
<td>0.56 = X/Y</td>
<td>0.32 = X/Y</td>
</tr>
<tr>
<td>V (mm/s)</td>
<td>125.93</td>
<td>251.86</td>
<td>377.79</td>
<td>503.72</td>
</tr>
</tbody>
</table>

Table 2 Having chosen option 2 from Table 1, Binder Jetting could be carried out at with either 500 or 525 DPI. Since 504.25 is nearer to 500, this is the ideal option

<table>
<thead>
<tr>
<th>Min DPI (Y)</th>
<th>500</th>
<th>Max DPI (Y)</th>
<th>525</th>
</tr>
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<td>% Accurate</td>
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<td>0.04114</td>
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<tr>
<td>Velocity [mm/s]</td>
<td>254</td>
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<td></td>
</tr>
</tbody>
</table>
**Bonus: Dithering**

Dithering the build has long been an established method of controlling print density in 2D applications. By dithering the drops, the machine seeks to minimise the chance of excess bleed of the ink, while still preserving the original image quality.

In Binder Jetting, dithering is done for the same reason, but, with BJT, you get an additional benefit: any chemical that is added to the binder has the potential to be added to the chemistry of the final part. If it cannot burn out cleanly in the furnace, or during the curing step, those residuals can affect the material properties of your part. The most affected chemical is carbon, as almost all binders are based on polymers with a carbon backbone.

Most dithering strategies fall into one of two categories: using different sized drops for the interior and exterior or using all the same sized drops, but removing some. In both cases, an outer shell of some voxel thickness is additively manufactured with full saturation, as we calculated earlier. This guarantees the part can be handled post-cure.

In the case of drops of multiple sizes, the machine takes advantage of binder nozzle flexibility. Most nozzle modules can generate a few different sized drops from a single type, so a smaller-sized drop might be selected to uniformly fill the interior. For droplet reduction when using standard drops, special filtering algorithms are employed to optimise the infill. Both methods achieve the same goal, in that less binder is used.

It is important to note that dithering is only possible when using binder nozzles with the right controls, and/or a software stack that supports directly working on voxels. Again, this is value engineering at work. To have the feature, you have to pay for the feature.

I hope you found this article useful and informative. If you still have questions about how to tune your machine and process, please reach out!

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Johnson and Johnson on medical device challenges for MIM components

MIM2022’s keynote presentation saw Gary Jaworek, Johnson and Johnson (J&J), New Jersey, USA, speak on the challenges faced in the manufacture of medical devices using Metal Injection Moulding [1]. Johnson and Johnson has a number of divisions which make a wide range of medical products that incorporate MIM components, the production of which are entirely outsourced. These medical products include tools for a range of medical purposes, such as tissue sealing and surgical stapling, and catheters for treating cardiac arrhythmia for surgical application in minimally invasive procedures. Fig. 1 shows a trio of tissue sealing instruments incorporating MIM components.

These minimally invasive instruments have MIM applications in articulation joint components, drive components, firing rod connectors, gears, gear boxes, shafts and end effectors. Typical articulation joints inside these instruments are shown in Figs. 2 and 3, with MIM gears inside the control handles visible. The challenge is that individual medical parts are now becoming smaller than 10 mm and often have non-uniform wall thicknesses and compound surfaces, which makes the location of ejector pins difficult. Features and tolerances are tiny; some parts may be long and only 0.375 mm thick, where flatness is crucial, and all critical requirements must be met. Every available tool must be used to eliminate process risks and ensure these instruments do not fail during use. Naturally, these components must go through the rigid quality and regulatory control procedures that are the norm for medical devices.

Though the MIM process is a very effective method for the production of large quantities of small parts...
with volumes in the hundreds of thousands, J&J has now recognised that Binder Jetting (BJT) could have distinct advantages over MIM in the medical device arena. The long times required for the mould making and mould qualification processes in MIM could be eliminated from the part manufacturing cycle by turning to BJT. According to Jarowek, this technology will, however, complement MIM in this market.

**Animesh Bose compares Binder Jetting and MIM**

Animesh Bose, Desktop Metal Inc, Burlington, Massachusetts, USA, presented a comparison of BJT and MIM [2]. Bose stated that while worldwide MIM production may reach a market value of about $4,000 million by 2024, the top ten countries produce around $1 trillion worth of metal parts every year. The market value of metal Additive Manufacturing is just a blip in this $1 trillion world. Until 2015, the thrust of the metal AM industry was in melt-based AM processes, –i.e., Laser Beam or Electron Beam Powder Bed Fusion (PBF-LB/EBI) – where each layer of the part is formed by melting powders using a beam of energy, followed by solidification as the beam moves on, creating the part in one step.

This melt and solidify process results in a non-isotropic structure in the part. New developments in powder-binder technologies, however, have led to the decoupling of the part shaping stage and formation of the final solid part, as more and more binder-based AM processes are developed, such as Material Extrusion (MEX), BJT, screen printing and other similar processes. These processes, explained Bose, are similar to the MIM process and can use MIM powders to make isotropic structures. MIM and MEX-based AM processes use a thermoplastic polymer-based binder, while, in BJT, the binder is thermoset. Both MIM and BJT use debinding and sintering to form the final part, but BJT, like other AM processes, does not require any tooling.

*Fig. 2 A typical articulation joint manufactured by MIM (Courtesy J&J)*

*Fig. 3 MIM gears inside the instrument-controlling handle (Courtesy J&J)*
Bose stated that in the BJT process, a binder is selectively deposited on a layer of powder to form one layer of the part at a time. The binder forms the bond that holds the particles and layers together. However, the BJT process needs a curing step to provide handling strength to the part and a depowdering step to remove loose powder from the parts before they are moved on to the debinding and sintering stages. After this, the parts may be finished in a similar manner to MIM parts.

In the Binder Jetting process, the powder itself can support the parts as they are built. The pictures in Fig. 4 show the standard method of additively manufacturing a mixture of parts (left) and a different method of orienting and stacking a mixture of parts to utilise the maximum space in the build box (right). The isotropic properties obtained after sintering are not affected by the orientation of the parts in the build box.

The BJT process also allows the manufacturer to use just the amount of material necessary to perform the function for which the part is designed. On the left of Fig. 5 is an original part design weighing 1.325 kg, while, in the middle, we see the lightweighted, modified BJT design weighing just 0.586 kg. This part would be impossible to produce by MIM. On the right is shown the positioning of a batch of parts in the build box. It is worth noting that BJT can also produce parts much larger than those possible by MIM.

Bose concluded that the BJT process can both be complementary to and serious competition for MIM. Recognising this, many MIM...
companies are proactively spending money on BJT technology.

**Unravelling sintering distortion after machining in the green state**

If you take a MIM part and machine a hole in the green state, what would happen to the hole after sintering? This unusual topic was discussed in a presentation by Levi M Rust from ARC Group Worldwide, based in Denver Colorado, USA [3]. Sintered parts are subject to unusual distortions depending on the moulding conditions, and distortions that can occur to holes and slots after the sintering are difficult to predict.

Fig. 6, left, shows an isometric view of a green MIM part with an arrow indicating the gate position. The part has eight slots of the same length, with uniform spacing between them. On the right is shown the part after machining in the green state. The parts in the study presented were made from L605 alloy and, after machining, they were sintered and HIPed to a density of about 9.05 g/cm³ or 98.3%. Distortions from the machined shape after sintering were measured and attempts made to compensate for the distortion identified by using a different machining pattern in the green state.

The green parts were machined to an elliptical pattern, based on the overall non-uniform shrinkage in the x and y directions of the part; this resulted in an unusual pattern of distortion. A circular hole resulted in a more uniform type of distortion with a variation of only ± 0.038 mm. Fig. 7, left, shows the measured variations on the machined circle with this variation and on the same hole after sintering and HIPing on the right. This pattern after sintering and HIPing shows a symmetric distortion pattern based on the position of the slots and the openings between the slots.

In the final test, a contoured profile was machined based on the ± 0.038 mm variation measured from the circular hole test. This resulted in an over-correction of the hole by ± 0.020 mm, but a decrease in contoured profile of 0.018 mm.

There are many potential applications for the knowledge gained in this study. These include:

- The ability to achieve near-machined tolerances with materials that are difficult or impossible to machine in the as-sintered state
- The machining of features which would be otherwise impossible to produce using MIM
A reduction in machining cycle time and tool wear

The ability to more easily prototype tool changes for tooling modification

Application of hot disc transient plane source for thermal conductivity evaluation in MIM: metal powders case study

Artem Trofimov, from Orton Ceramic Foundation, Westerville, Ohio, USA, presented a novel concept in his paper on the application of a hot disc transient plane source for thermal conductivity evaluation in the MIM industry [4]. Thermal conductivity is a basic material property that changes when there are changes in the material. Thermal conductivity is given by the equation:

\[ \lambda = \alpha \rho C_p \]

Where:
- \( \lambda \) stands for thermal conductivity
- \( \alpha \) for thermal diffusivity
- \( \rho \) for the density of the materials
- \( C_p \) for specific heat capacity

The most common way to measure the specific heat capacity is using differential scanning calorimetry, while the thermal diffusivity is measured by laser flash technique. These methods have sample size restrictions and laser flash, for example, can only be used with solid materials and not powders or liquids. In Orton Ceramic’s study, three individual techniques used for measuring these parameters introduced three measurement errors into the calculated thermal conductivity value.

Orton Ceramic then used a hot disc transient plane source (TPS) method to directly measure the thermal conductivity and thermal diffusivity from a single measurement. The only sample preparation requirement for this method is a flat surface, with minimal restrictions on sample size. This allows the use of this method on powders, binders, feedstock (maybe, with some preparation), green parts, solvent and thermally debound parts, as well as sintered parts. Parts may be tested at temperatures between -196°C and 800°C.

The TPS method uses a nickel double spiral (hot disc) sensor sealed in Kapton films, resulting in a thickness between 60-80 µm. The disc is both the heat source and a dynamic temperature sensor, capable of measurements of thermal conductivity between 0.01-1800 W/m/°K. Measurement times range from a few seconds to a few minutes. Fig. 8 shows a TPS sensor and how it is used on a solid machined metal piece.

When powder measurements are carried out, the conductivity will change depending on the medium.

Fig. 8 A TPS sensor (left) in use on a solid metal piece (right) (Courtesy Orton Ceramics)

Fig. 9 First cylinder filled with powder (left) and two holders with powder with the sensor in between (right) (Courtesy Orton Ceramics)
between the powders as well as the shape, size and distribution of the powders. When taking measurements on powders, the powder is first filled in a cylindrical sample holder and levelled off. The TPS sensor is placed on the powder and a second sample holder is placed on top of the first and then filled up with the same powder. Fig. 9 shows a filled bottom sample holder on the left and the two cups filled up with the sensor between the powder on the right.

In the case of green parts, two pieces with flat surfaces need to be used. No data were presented on MIM parts, but data on different sizes of powders, and the compacted powders, were presented. This author would expect that, for green MIM or additively manufactured parts made using binders, measurements would have to be carried out in a similar way. Fig. 10 shows the measurement set up, with two discs made with compacted fine powders.

Reducing shrinkage in large stainless steel BJT parts using novel coated metal powders

Alexander Paterson of ExOne (now part of Desktop Metal), North Huntington, Pennsylvania, USA, presented work carried out in collaboration with Tundra Companies, White Bear Lake, Minnesota, USA, to compare the Binder Jetting (BJT) of standard 316L stainless steel with the BJT of stainless steel powder modified by Tundra [5]. Tundra produces a special coating material, TundraKoat, said to improve the packing density of any particulate material to > 80%, which can result in optimised properties for the material. In this case, the partners modified a 316L stainless steel powder, which was used to make parts and rods from which tensile bars were machined.

The BJT process used for the standard powder (22 µm) had to be modified to make parts from the Tundra powder. The standard powder is built with a layer thickness of 50 µm, however the Tundra powder, where the particle size was 50 µm had to be additively manufactured with a
layer thickness of 75 µm. The change in the layer thickness and powder particle size also caused a change in the binder set time from five seconds for the standard powder to thirty seconds for the Tundra powder. The Tundra powder resulted in a higher packing ratio and compressibility of the powder than the regular powder, which showed a dustier surface. The irregular edges on the build plate for the Tundra powder was a result of the highly cohesive behaviour, which caused shear stresses on the lips of the build box. The printable build space was unaffected. Fig. 11 shows the build surface for the standard powder and the Tundra powder.

The parts were sintered using a standard 316L profile. Round bars were machined to make the tensile specimen used to obtain the data in Table 1. The Tundra parts showed properties on the higher end of that for the standard powder.

The powder loading for the Tundra powder was 70%, while the standard powder reached 55%. The effect of the low shrinkage is apparent in parts that were 300 mm long, where the Tundra powder resulted in 27 mm less shrinkage because of the higher powder loading.

### Production of MIM permanent magnets from recycled NdFeB powder

Rare earth permanent magnets (REPM) are key components for efficient energy conversion for electromobility, green energy, as well as many everyday technologies we can no longer do without, such as smartphones, speakers and more. Only 10% of the REPMs are made in the European Union, with the majority of the remainder coming from China. Furthermore, current mining and manufacturing methods are causing damage to both the environment and the health of people in these areas.

SUSMAGPRO would like to create a circular economy by recovery, reprocessing and reuse of REPMs in new products. Their goal is that every fourth REPM used in Europe should be a recycled one by the year 2027. A typical microstructure and the schematic picture of the NdFeB magnet is shown in Fig. 12.

The process of recycling old magnets to produce new ones requires that an end-of-life magnet be decomposed into powder by the Hydrogen Processing of Magnetic Scrap (HPMS) process. During this process, the Nd-rich grain boundary phase forms a hydride, which causes it to expand. The expansion of the grain boundary

<table>
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<th>Tensile Data</th>
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<th>Tundra</th>
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<tr>
<td>Shrinkage Rates (%)</td>
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<td>9-10</td>
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Table 1 Properties obtained after sintering

Fig. 12 Left: The typical microstructure of the NdFeB magnets, right: A schematic of the same structure (Courtesy Pforzheim University)
phase forces the structure to fall apart. After the hydride formation period, the result is a friable, demagnetised powder, comprising a set of Nd$_2$Fe$_{14}$BH$_x$ irregular particles that are of the order of 10 µm in size and NdH$_{2.7}$ particles smaller than 1 µm. Fig. 13 shows a SEM of the powders.

Working with neodymium, however, is complicated by its affinity for oxygen and liability to oxidise quickly. The resulting powder must therefore be coated immediately to prevent oxidation of the powder. After preparing the powder, it was mixed in an extruder with polymeric binders and the resulting feedstock was extruded. Then, an extrusion die was chosen with the desired cross-section. The strand was cut to the desired length and the parts were subsequently debinded and sintered.

Conclusion

This is a report on the selected presentations I found especially interesting after more than the twenty years attending the MIM conference. Limiting myself to a selection, while difficult, was necessary due to the restraints of this format, and does not reflect on the merits of those presentations not reviewed here. It is innovative ideas such as these that make it worthwhile to attend these conferences. My thanks to each of the presenters and to the MPIF for their support in preparing this article.

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References


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Ceramics in new dimensions: Additive Manufacturing at CeramTec

No matter which market report you choose to believe, all recent analysis of the ceramic AM market points to major growth. But this is still an emerging technology, and in terms of its commercial development, ceramic AM is said to be five years behind metal AM. Now, as global manufacturers of high-performance ceramics enter the market, an even faster acceleration in technology adoption is promised. Here, Claus Falkner, of CeramTec, a producer of technical ceramics by processes that include Ceramic Injection Moulding, explores the benefits of ceramic Binder Jetting and considers the process as a compelling solution for complex parts.

CeramTec, headquartered in Plochingen, Germany, ranks among the largest international manufacturers of ceramics for technically demanding applications. The company began its Additive Manufacturing journey in 2015 with the aim of building up a division for the production of ceramic components. Owned by CPP Investment Board Europe S.àr.l, and BC Partners as of August 2019, CeramTec reported an annual turnover of almost €553 million ($592.2 million) in 2020, despite the difficult market situation created by COVID-19, and currently employs around 3,400 staff at twenty production sites in Europe, North and South America, and Asia. This article will highlight CeramTec’s AM capabilities and present the Binder Jetting (BJT) process as a compelling production solution for ceramic parts.

For CeramTec, the decision to invest in an in-house ceramic AM unit in 2015 ties in deeply with the company’s strategy of diversification in all business areas, as well as its DNA of innovation. A dedicated and continued focus on R&D has been at the core of the business since its beginnings in the early 20th century, with customer requirements and the ability to provide added value in a rapidly changing market space the key guidelines for development.

When the company first began integrating its ceramic AM capabilities, a technical centre was set up at its Lauf site in Bavaria to develop the process, from BJT to the final component, including thermal treatment with a final sintering process and optional surface finishing.

Fig. 1 CeramTec’s site in Lauf, Germany (Courtesy CeramTec)
Innovations in silicon carbide ceramics

At the beginning of 2021, CeramTec’s BJT process for the production of parts in a specific technical ceramic material was officially launched, enabling the business to combine the special material properties of silicon carbide ceramics (SiSiC) with the advantages of the relatively fast, cost-effective BJT process.

SiSiC is a versatile, two-component material comprising a metallic phase with silicon, making it electrically conductive and affording it a range of beneficial properties including superior rapid cooling, rapid heat resistance, wear resistance, oxidation resistance, high bending strength and a long service life. It also has excellent hard-wearing properties and is not only the lightest, but also the hardest ceramic material. It stands out for its thermal conductivity and has virtually no thermal expansion. The latter is particularly important for the semiconductor industry, which uses SiSiC wafer chucks in chip production.

“SiSiC is a versatile, two-component material comprising a metallic phase with silicon, making it electrically conductive and affording it a range of beneficial properties including superior rapid cooling, rapid heat resistance, wear resistance, oxidation resistance, high bending strength and a long service life.”

Most importantly, this material demonstrates very little shrinkage during the sintering process, retaining relatively stable dimensions, which also makes it suitable for extremely large components such as structural parts for machines or nozzles, for example in the chemical industry. For CeramTec, the decision to work with binder jetted SiSiC, which allows for the production of lightweight components with particularly high stiffness and strength, enabled a wide range of interesting applications. The company’s in-house developed SiSiC material, ROCAR®3D, is the result of a fine-tuning process which optimised the properties of additively manufactured SiSiC components in such a way that the material characteristics correspond to the properties of conventionally manufactured components to within a few percentage points.

The process: ceramic Binder Jetting

The original Binder Jetting process was developed through an MIT (Massachusetts Institute of Technology) project in the late 1980s. The principle is similar to laser sintering for metal, but uses a jetted binder – instead of a laser beam – to ‘weld’ the material together. Essentially, structures are manufactured through the application of droplets of liquid binding agent (phenolic resin) in a very fine jet onto a powder bed of ceramic powder grains to weld them together in the pattern defined by the STL file. Layer by layer, this process is repeated until a ceramic green body is obtained, which then undergoes sintering to obtain ceramic properties.

Binder Jetting is one of the most scalable AM technologies and is being used to produce big components from a variety of materials, including ceramics. It has a number of advantages such as scalability, design freedom and throughput. With material thickness from 2 mm to 35 mm and hole diameters from...
2 mm, ceramic design options are wide ranging. One key benefit is that BJT works without support structures. The self-supporting powder bed enables the production of geometrically complex parts as they are required by CeramTec’s customers. This can, for example, include the AM of parts containing internal cavities, such as cooling channels, which can even be curved.

As SiSiC is significantly lighter than steel, the process also lends itself to lightweight construction. Through the use of clever design for BJT, similar part strengths and structural properties to those of steel parts can be achieved with far less weight in SiSiC. In the future, as energy efficiency becomes more important, this will become ever more relevant in the industrial context. An example of high-value applications are rotating components – such as pump impellers – which have traditionally been made of steel. Being able to deploy a much lighter ceramic rotating component means that less energy has to be applied to drive the part. The larger such rotating components become, the bigger an issue part weight presents, making ceramic a very interesting option – and ceramic AM is key to opening up these new fields of application where ceramic has previously not been used.

While CeramTec currently uses its AM facilities primarily for the development and production of prototypes, starting with a batch size of one, and components in small series, the BJT process was also chosen with a view to scalability and ease of replicating the current AM unit at the company’s Lauf site in other production facilities. The overall Binder Jetting mechanism enables speed and a considerable fabrication throughput, based on the technology working by laying down a layer of ceramic powder at once and the advantage of depositing the binder using an inkjet-like buildhead. This is a fast process that can easily be scaled up when using several jetting heads to increase throughput.

Fig. 3 A ceramic BJT build in process at CeramTec (Courtesy CeramTec)

Fig. 4 Ceramic BJT parts on a sintering tray (Courtesy CeramTec)
In ongoing process development, CeramTec is also looking at how to partially automate Binder Jetting to make the process, which in its current form requires significant manual work between its individual production steps – namely the removal of parts from the powder bed – even more efficient.

Case study: SiSiC for heating
Harnessing the advantages of AM, such as enabling fast delivery times for small quantities and sophisticated geometries, CeramTec uses ceramic Binder Jetting to produce heating elements for several applications such as welding and drying.

“As no set-up costs are incurred, the cost-effective production of individual pieces or small series can easily be supported. In the unlikely event of a failure, the use of AM means that an exact replacement is available at short notice.”

Crucially, these parts take advantage of the specific properties of SiSiC (i.e., the combination of high thermal and electrical conductivity with other characteristics of high-performance ceramics, namely high hardness and chemical resistance). Since emitters need to be manufactured for each product specifically, they require a wide range of complex geometries in small quantities, making them an ideal application for AM as a flexible, customisable production technology. As no set-up costs are incurred, the cost-effective production of individual pieces or small series can easily be supported. In the unlikely event of a failure, the use of AM means that an exact replacement is available at short notice.

Further ceramic AM applications
SiSiC is also a key material for semiconductor manufacturers due to...
its extremely low thermal expansion. Photolithography systems for semiconductor manufacturing are becoming more sophisticated and component suppliers need to be able to provide products of the highest quality to meet the current and future demands in chip production.

In 2020, the global semiconductor industry recorded a turnover of $440 billion, driven by increasing digitalisation of the products we use every day, and developments in the technologies around artificial intelligence, 5G, emobility and the internet of things, which all rely on semiconductor technology.

In recognition of the demand for semiconductors, the European Commission launched the 'European Alliance on Processors and Semiconductor Technologies' in July 2021. The aim of the alliance is to increase the European share of global semiconductor production to 20% by 2030 and to expand manufacturing capacity to develop state-of-the-art semiconductor chips in the 5–2 nanometer range.

CeramTec has long-standing expertise in manufacturing SiSiC plates which are used as the basis for electrostatic wafer chucks in semiconductor machines for the production of chips and AM enables the company to act as an innovative partner for its customers in this industry. The flexible design options offered by AM are key here as SiSiC components can be produced in unique product geometries that are not supported by other manufacturing processes.

Ongoing integration of ceramic BJT in manufacturing processes

Customer requirements drive innovation. Developing and growing the established BJT process is therefore in CeramTec’s focus. As most BJT machine manufacturers do not, as yet, focus on ceramics as a major material, setting up BJT machines requires some adaptation with regard to the fine-tuning and layer thickness of the used material. With this in place, there is potential to reproduce this set-up in other company locations...

“As most BJT machine manufacturers do not, as yet, focus on ceramics as a major material, setting up BJT machines requires some adaptation with regard to the fine-tuning and layer thickness of the used material. With this in place, there is potential to reproduce this set-up in other company locations...”

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Understanding the carbon footprint of injection moulding machines

Arburg GmbH + Co KG, Lossburg, Germany, has been working intensively on sustainability and resource efficiency for a very long time. As the supplier of the widely used Allrounder line of injection moulding machines, the company is increasingly active in evaluating climate protection activities along the entire value chain for its customers. On the basis of ISO TS 14067:2018 – a standard that defines a product’s greenhouse gas emissions or Product Carbon Footprint (PCF) – Bertram Stern, Sustainability Manager at Arburg, reports on how the PCF and specific energy requirements of Arburg injection moulding machines can be calculated.

Under the European Union’s Green Deal, the reduction of the carbon footprint of companies and their products is being strongly promoted. To meet new, strict legal requirements and achieve climate-neutral production by 2050, companies will have to significantly increase energy and resource efficiency. Accordingly, sustainability is currently an important strategic issue for many European manufacturers.

Enshrined in law: carbon neutrality in Germany by 2045

The German Climate Protection Act goes one step further and calls for a 65% reduction in CO₂ emissions by 2030 and carbon neutrality by 2045. The internationally recognised standard for CO₂ accounting – the Greenhouse Gas Protocol – considers different emission areas (scopes).

Injection moulding machines are Scope 3 assets, which include indirect emissions from upstream and downstream business processes. As a machine manufacturer, Arburg is actively and comprehensively involved in carbon accounting to provide reliable and comparable indicators and meet the ambitious climate targets. This is also evidenced by its above-average ‘B’ score in the Carbon Disclosure Project (CDP).

Product Carbon Footprint

In contrast to the Corporate Carbon Footprint (CCF), which is calculated for an entire company on an annual basis, the Product Carbon Footprint (PCF) includes the quantities of greenhouse gases emitted and removed over the entire service life of a product. Expressed as CO₂
The first relevant question for injection moulders is the carbon footprint with which the machine arrives at the plant. In its ‘cradle to gate’ analysis, Arburg draws the associated system boundary from raw material extraction through the manufacturing phase to the factory gate. However, this period only accounts for around 5% of CO₂ emissions. Over the entire product lifecycle (‘cradle to grave’), most of the PCF is generated during the use phase at the customer’s premises, in addition to emissions during distribution and disposal.

Arburg records CO₂ emissions up to the finished injection moulding machine in four process steps: painting or coating; mechanical machining and processing; electric production and assembly. The raw materials used and the respective electricity requirement can be assigned to this operational sequence and the other phases in the product life cycle (Fig. 2).

The parts list of an injection moulding machine can consist of up to 11,000 individual items, down to the individual screw. For better manageability, Arburg groups raw materials into eight material groups. Accordingly, an Allrounder consists of more than 55% plastic-coated cast iron, and another 35% or so of steel and sheet metal (hot-treated, painted, plastic-coated, or untreated). Plastic components, drives and electronic components account for only about 7% of the total weight.

The material groups differ significantly in terms of the CO₂ emissions generated during their production. However, a weighted mean value can be determined along the lines of the distribution. This so-called ‘emissions factor’ is around 1.83 [kg CO₂ equivalent/kg product] for an Allrounder. The CO₂ equivalent for the complete injection moulding machine thus corresponds to the emissions factor multiplied by the product weight specified in the data sheet (Table 1).

A hybrid Allrounder 570 H with a clamping force of 2,000 kN and a net weight of 8,300 kg, therefore, causes equivalent, the PCF is an important indicator in the life cycle assessment. The guidelines for quantification and reporting are provided by the international standard ISO TS 14067:2018. The first relevant question for injection moulders is the carbon footprint with which the machine arrives at the plant. In its ‘cradle to gate’ analysis, Arburg draws the associated system boundary from raw material extraction through the manufacturing phase to the factory gate. However, this period only accounts for around 5% of CO₂ emissions. Over the entire product lifecycle (‘cradle to grave’), most of the PCF is generated during the use phase at the customer’s premises, in addition to emissions during distribution and disposal. Arburg records CO₂ emissions up to the finished injection moulding machine in four process steps: painting or coating; mechanical machining and processing; electric production and assembly. The raw materials used and the respective electricity requirement can be assigned to this operational sequence and the other phases in the product life cycle (Fig. 2).
raw material-related emissions of around 15,190 kg of CO₂ during its manufacture. For a 3,300 kg size 370 Allrounder with 600 kN clamping force, the CO₂ equivalent is around 6,040 kg.

**CO₂ from electricity used during manufacture**

In the manufacturing phase, the electricity requirement also contributes to the PCF. In relation to the year 2020, the basis for standardised calculations is an electricity requirement of 878.94 kWh per 1,000 kg of product and an emissions factor of 0.366 (kg CO₂ equivalent per kWh) for the German electricity mix (Table 2).

On the basis of the German electricity mix, the electricity requirement is 2,900 kWh for the Allrounder 370 H, with a CO₂ equivalent of around 1,160 kg. For the Allrounder 570 H, the electricity requirement is therefore 7,295 kWh and the emissions around 2,670 kg CO₂.

However, this example calculation cannot be applied 1:1 to Arburg, as the company manufactures around 60% of its Allrounder components itself. Arburg makes its products exclusively at its central location in Lossburg. This involves the use of carbon-neutral renewable energies such as photovoltaics, wind energy and geothermal energy, as well as combined heat and power. Since 2016, electricity purchased regionally has come entirely from ecological sources. This means that around 53% fewer emissions are produced in terms of electricity during the manufacturing phase of an Arburg injection moulding machine than the German average.

If the raw material and electricity-related emissions are added, the total CO₂ equivalent for a cradle to gate analysis is 6,530 kg for the Allrounder 370 H and 16,430 kg for the Allrounder 570 H (Table 3).

For comparison: In Germany, each person generates an average carbon footprint of around 12,000 kg per year, depending on factors such as consumption, mobility, housing and nutrition.

### Table 2 Electricity-related CO₂ emissions in the production of an injection moulding machine can be calculated on the basis of the German electricity mix (0.366 for the year 2020) [Courtesy Arburg]

<table>
<thead>
<tr>
<th>Series*</th>
<th>Weight (in kg)</th>
<th>Electricity requirement* (in kWh)</th>
<th>Emissions factor**</th>
<th>CO₂ equivalent manufacture (in kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allrounder 370 H</td>
<td>3,300</td>
<td>2,900</td>
<td>0.366</td>
<td>1,160</td>
</tr>
<tr>
<td>Allrounder 470 H</td>
<td>4,700</td>
<td>4,130</td>
<td>0.366</td>
<td>1,510</td>
</tr>
<tr>
<td>Allrounder 570 H</td>
<td>8,300</td>
<td>7,295</td>
<td>0.366</td>
<td>2,670</td>
</tr>
</tbody>
</table>

* Standardised electricity requirement: 878.94 kWh/1,000 kg product
** Basis: German electricity mix (2020)

### Application-related carbon footprint in use

Around 95% of the PCF of an injection moulding machine is attributable to its use phase. How many emissions it actually produces in daily

![CO₂ equivalent](image-url)
operation depends on a large number of factors. Already during the selection of the material being injected, a product’s design, and the construction of the injection mould, important decisions are made. An important application-related parameter here is the specific energy requirement (kWh per kg), which is calculated from power consumption per material throughput. As a rule of thumb, the shorter the cycle time and higher the shot weight, the smaller the specific energy requirement and better the CO₂ equivalent.

### Machine equipment crucial

A crucial aspect for the specific energy requirement is whether the injection moulding machine has an electric, hybrid or hydraulic drive. Whether one or two-circuit pump technology or hydraulic accumulators are used and options such as servo-electric dosing or ejection are part of the equipment also play a role.

Features that enable simultaneous, dynamic and fast movements and thus short cycle times have a positive effect on the carbon footprint during use. The same applies to the screw diameter and installed power – the greater the shot weight and the smaller the power consumption, the better. In summary: machine equipment that is precisely adapted to the requirements and processes can significantly improve the energy requirement. Arburg supports its customers in this task with a wealth of expertise in application and process technology and exploits the advantages of modular machine technology.

### Measuring the energy requirement in accordance with EUROMAP 60.2

The EUROMAP 60.2 recommendation forms the basis for determining the energy requirements of injection moulding machines in a customer-specific process. To enable an objective comparison of different machine concepts, measurements are taken and documented at average power consumption under uniform specifications over a defined area. The values depend on the machine technology as well as the capacity utilisation and type of application. For example, the specific energy requirement for the production of technical moulded parts in smaller quantities is significantly greater per se than for the production of fast-moving packaging items (Fig. 4).

The measurement results show that, in comparison to standard hydraulic machines, electric machines require around 50% less energy. The lower the material throughput, the more significant the differences – but energy-optimised hydraulic machines can also significantly reduce the carbon footprint.

### Application example

Arburg examined various scenarios as part of a practical application: Hydraulic and electric Allrounders from the S and Alldrive series were used in the three sizes – 370, 570 and 820 – with clamping forces of 600, 2,000 and 4,000 kN. A distinction was made between hydraulic drive systems with two-circuit pump technology (T2) and electric drive systems in the ‘Comfort’ performance variant.
Two items were produced: a technical item made of PA66 (GF30) in a cycle time of 30 seconds at 50% plasticising capacity, and a packaging item made of PP in a cycle time of five seconds at 100% plasticising capacity (Table 4). The CO$_2$ emissions were calculated on the basis of the German electricity mix.

The electric Allrounder 820 A with a throughput of 115.2 kg/h produced emissions of 1.07 kg CO$_2$ per kg of plastic material while injection moulding the packaging item. The size 370 electric machine emitted around twice as much (2.13) when injection moulding the technical article with a throughput of 4.2 kg/h. With the hydraulic Allrounder 370 S, this value was as high as 4.43.

So much for the sample study. Depending on the case of application, there may be deviations from this. In individual cases, the actual power consumed depends on the duty cycle, capacity utilisation, and efficiency of the connected loads. These factors are, in turn, influenced by the injection moulding process. However, it can generally be said that the energy requirement for both types of drive decreases as material throughput increases. In any case, an electric machine produces around 50% fewer CO$_2$ emissions. The same result can be seen when the CO$_2$ emissions are calculated consistently on the basis of the material throughput.

The CO$_2$ emissions for the production of the injection moulded granulate and other loads such as peripheral devices for temperature control of the moulds or hall air conditioning (waste heat and cooling) are not included in this analysis. The energy requirements and thus the CO$_2$ emissions of the peripheral devices increase sharply, especially for technical items, and may even exceed those of the injection moulding machine on a proportional basis. The carbon footprint calculated for a single injection moulded part is another interesting parameter.

**Conclusion**

A meaningful cradle to gate carbon footprint can be determined for injection moulding machines. Raw materials have a roughly tenfold greater impact on the product carbon footprint than electricity consumption during the manufacturing phase. Local supply chains, a high degree of in-house production depth and the use of renewable energies can have a positive impact on the footprint.

The PCF during the use phase depends on many factors. A specific case study is required here. As a rule, the specific energy requirement of an injection moulding machine decreases with its capacity utilisation. In addition, electric machines generate up to around 50% less CO$_2$ emissions than hydraulically driven ones, depending on the equipment and material throughput.

The aim for the future is to be able to calculate a scientifically sound, holistic life cycle assessment for injection moulding machines. This will require a much greater effort. This is precisely what the Institute of Plastics and Circular Economy (IKK) at Leibniz University in Hanover, headed by Prof Hans-Josef Endres, is working on in collaboration with Arburg, among others.

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The maths in the magic: Calculating the sintering shrinkage of MIM parts

Newcomers to Metal Injection Moulding never cease to be amazed when they see that green parts uniformly shrink during debinding and sintering into a finished part. This calculated shrinkage, which is what enables products to conform to an engineer’s blueprints, can appear pretty magical. It is, of course, simply a matter of mathematical calculation. In this article, Dr Chiou Yau Hung (Dr Q) and James Chao, from You neeD Technology Office, Taiwan, encourage you not be scared off by the mathematics and discover the calculations at the heart of MIM.

In 1972, Parmatech applied for the first patent for Metal Injection Moulding. From these beginnings, no one could have imagined the MIM process as the indispensable metal parts manufacturing method it has become fifty years later, without which many of the modern products we rely on would either be impossible to produce, or quite different. What was originally a process reserved for use with refractory materials and hard-to-process alloys must now meet demands for millions of parts per day for applications in computers, communications and consumer electronics (3C), automotive, aerospace, medical and far beyond.

Anyone new to MIM technology might marvel at the use of plastic injection moulding machines to form these metal parts in industrial quantities. They might be especially amazed when they see that the green parts, after debinding and sintering, can be uniformly shrunk into a finished part. This calculated shrinkage, which allows products to conform to an engineer’s blueprints, can appear pretty magical.

In this article, please follow me as I show you how this magic MIM shrinkage is calculated with a simple mathematical model. Don’t be scared off by the mathematics; here, we will only use simple calculations, which can be undertaken by anyone in a Microsoft Excel sheet. Readers must note that this model has been created to reflect the ideal manufacturing situation and variations in powder size suitability, equipment, etc. must be considered when replicating these calculations.

Fig. 1 Today the Metal Injection Moulding industry meets the demand for millions of parts per day for applications in computers, communications and consumer electronics (3C), automotive, aerospace, medical and far beyond.
Calculating part shrinkage

Archimedes formula for density

To start, we need to understand the Archimedes formula for density:

\[ \rho = \frac{M}{V} = \frac{\sum M_i}{\sum V_i}, \rho = f(T) \]
[eqn. 1]

Here, \( \rho \) is the density of a material, \( M \) is the mass of a material, and \( V \) is the volume of a material. The number of different materials present when there are too many types of material, a grouping calculation reduction can be used to merge the volume or weight of several different materials. Finally, \( T \) is temperature (°C, °F, or K). 15–30°C are preferred for testing.

We then have to understand the volume of a cuboid:

\[ V = x \times y \times z = x^3 \]
[eqn. 2]

x, y, z = the edge length of the cube in each direction. When the object is a cube, its volume is equal to a simplified calculation method of this model when \( x = y = z \) and the volume of the cube of equilateral length = \( x^3 \)

Defining of cavity size: Oversize Shrinkage Factor (OSF)

We now need to understand cavity size versus the size of the final sintered part:

\[ x_s \times OSF = x_C \]
[eqn. 3]

Here, \( S \) = size of the part after sintering, \( C \) = cavity of the part. The green part, after injection, will naturally be able to be removed from the cavity due to the shrinkage of the MIM feedstock. Therefore, if the design value of OSF is 1.165, it is natural to import equation (3) to convert the size of the cavity.

When assuming that the shrinkage of the raw blank is negligible when it is removed from the mould, equation (4) can be changed to:

\[ x_s \times OSF = x_G \]
[eqn. 4]

Here, \( G \) = green part. If metal powders and binders are very uniformly dispersed in the feedstock, we can accept \( x_s = x_C \). In general, \( x_s < x_C \) is correct. Green parts can be detached from the cavity after injection moulding. In fact, a green part will still encounter some shrinkage after the feedstock cools. My suggestion is to use \( x_s = x_C \) as a simple calculation.

According to the assumptions of Equation (4), the small shrinkage of the green part after it is removed from the cavity is ignored when the injection process is finished. The relationship between the design dimensions of the MIM part and tooling is shown in Fig. 2.

Volume ratio of powders and binders

The ratio of powders and binders of MIM green parts can be estimated, based on the OSF values we have selected. We still import equation (4) as a cube part. At the same time, the following assumptions must be noted, when performing the actual MIM process:

Metal powder size

Metal powder particle size for MIM is \(< 45 \text{ um} \) and the optimal particle size range is \( d_{10} > 2 \text{ um} \), \( d_{50} = 9.8 \text{ um} \), and \( d_{90} < 22 \text{ um} \).
Calculating part shrinkage

**Powder/binder separation**
MIM powders and binders are evenly distributed and uniform after injection moulding. When we observe black marks on, or under, the surface of a green part, that location will sink after sintering. The main reason is that the high shear force of the injection press or cavity thickness change leads to the separation of powders and binders. The black mark phenomenon is observed where there is more binder and this causes the affected areas to sink.

**Debinding and sintering conditions**
The temperature of debinding and sintering is uniform and atmospheric pressure and flow is stable. This means selecting a high-performance sintering furnace with automated program controls.

**Distortion during sintering**
Dimensional changes in the sintered part, due to phase changes of material in the sintering process, are ignored. In practice, the effects of material phase changes can be corrected in post-processing procedures.

**Metal evaporation during sintering**
Metal evaporation losses during the metal sintering process are ignored. In practice, the effects of material in the sintering process, sintered part, due to phase changes of material in the sintering process, are ignored. The volume of metal powders and binders should be equal to the cavity volume. Therefore, here it is assumed that the stainless steel is 17-4PH material (15 kg powders) and that the binders are seven different types comprising Polyformaldehyde (POM), Polypropylene (PP), High Density Polyethylene (HDPE), Ethylene Vinyl Acetate (EVA), Paraffin Wax (PW), Stearic Acid (SA), and 1010 (BASF antioxidants). The individual binder weight ratios are: 88.25:25:1:1:4:1. We calculated, when OSF = 1.165, each binder weight. The third decimal place, following the decimal point, is calculated using the 4th rounding and 5 system method.

Now, we start the calculation. The calculation program uses a spreadsheet to perform a more factory-appropriate application. Looking at the appropriate ASTM table, we know that the density of 17-4PH is 7.85 g/cm³; the weight of the 17-4PH stainless steel metal powder in this project is 15,000 g = 15 kg.

According to OSF = 1.165, we first calculate the volume ratio of binders. We know the metal powder volume: binder volume = 17-4PH: binder = 63.2:36.8; So, \( \frac{V_{\text{m}}}{V_{\text{b}}} = 15,000 \text{ g } (7.85 \text{ g/cm}^3) = 1,910,828 \text{ cm}^3 \). Then, we can get \( V_{\text{b}} = 1,910,828 \text{ cm}^3 / 63.2 \times 36.8 = 1,112,634 \text{ cm}^3 \).

<table>
<thead>
<tr>
<th>Cavity Volume (10 x 10 x 10 mm³)</th>
<th>Metal (Solid) Volume ( V_s )</th>
<th>Binder Volume ( V_b )</th>
<th>OSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>700</td>
<td>300</td>
<td>1.126</td>
</tr>
<tr>
<td>1000</td>
<td>675</td>
<td>325</td>
<td>1.140</td>
</tr>
<tr>
<td>1000</td>
<td>650</td>
<td>350</td>
<td>1.154</td>
</tr>
<tr>
<td>1000</td>
<td>632</td>
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<tr>
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<td>500</td>
<td>1.259</td>
</tr>
<tr>
<td>1000</td>
<td>450</td>
<td>550</td>
<td>1.305</td>
</tr>
</tbody>
</table>

Table 1 List of metal powder/binder ratios used in calculating the OSF

**Weight ratio of powders and binders**
Actual factory operations do not perform volumetric measurements of powders and binders, so individual densities of substances must be imported to assist in the calculation to speed up the operation. Therefore, here it is assumed that the stainless steel is 17-4PH material (15 kg powders) and that the binders are seven different types comprising Polyformaldehyde (POM), Polypropylene (PP), High Density Polyethylene (HDPE), Ethylene Vinyl Acetate (EVA), Paraffin Wax (PW), Stearic Acid (SA), and 1010 (BASF antioxidants). The individual binder weight ratios are: 88.25:25:1:1:4:1. We calculated, when OSF = 1.165, each binder weight. The third decimal place, following the decimal point, is calculated using the 4th rounding and 5 system method.

Now, we start the calculation. The calculation program uses a spreadsheet to perform a more factory-appropriate application. Looking at the appropriate ASTM table, we know that the density of 17-4PH is 7.85 g/cm³; the weight of the 17-4PH stainless steel metal powder in this project is 15,000 g = 15 kg.

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Calculating part shrinkage

Assuming that binder materials are not vapourised during a mixing process, we know how to obtain the volume of the total binder = 1,112.634 cm$^3$.

Each binder density is: POM = 1.4 (g/cm$^3$); PP = 1 (g/cm$^3$); HDPE = 1 (g/cm$^3$) = EVA ; PW = SA = 1010 = 0.95 (g/cm$^3$). All of the data have now been simplified. We can calculate the density value of the binder according to the design level of 100 g.

The individual volume of the binder should be $V_{\text{POM}} = 88/1.4 = 62.857$ (cm$^3$); $V_{\text{PP}} = 2.5/1 = 2.5$ (cm$^3$); $V_{\text{HDPE}} = 2.5/1 = 2.5$ (cm$^3$); $V_{\text{EVA}} = 1/0.95 = 1.053$ (cm$^3$); $V_{\text{SA}} = 4/0.95 = 4.211$ (cm$^3$); $V_{\text{SA}} = 1/0.95 = 1.053$ (cm$^3$). Volume of total binder = 2.857 + 2.5 + 2.5 + 1 + 1.053 + 4.211 + 1.053 = 74.12 (cm$^3$), and density of total binder $V_{\text{Binder}} = 100 = 100$ g / 74.174 cm = 1.349 g/cm$^3$. Therefore, when the overall weight of the binder must be $W_{\text{Binder}} = 1,112.634$ cm$^3$ x 1.349 g/cm$^3$ = 1,501.119 g.

- Metal weight:Binder weight = 1,5000 g:1,501.119 g = 90.9:9.1
- Each binder constituent weight is: $M_{\text{POM}} = 1,501.119/(88/100) = 1321$ (g); $M_{\text{PP}} = 1,501.119/(2.5/100) = 37.5$ (g); $M_{\text{HDPE}} = 1,501.119/(1/100) = 15$ g; $M_{\text{EVA}} = 1,501.119/(1/100) = 15$ g; $M_{\text{SA}} = 1501.119/(4/100) = 60$ (g).

Fig. 3 is a screenshot of a table taken from Microsoft Excel. Readers can make this table by associating the results of the upper number calculations themselves.

Revised verification and correction

Some problems in the calculation process include how do we set up decimal points? Some readers may want to include more digits, thinking that the density of the material should be as accurate as possible. This is a divisive point for engineering applications and scientific research, but the second decimal place of the data is enough to satisfy engineering applications.

Another question is which value is correct for the theoretical density of a material? Or do you refer to the historical results of sintering in your factory? A helpful practice of the Japanese Powder Metallurgy Association (JPMA) is the publishing of a product quality report for all Japanese members every year. This can be used to gather average density and dimension statistics for MIM products from various materials. All members can refer to this as a benchmark for calculation.

In a production line, weight and dimension are closely related. In fact, while the dimensions of a green part may not reflect the dimensions of the final sintered part, the state of tooling and cavities can be understood through the measurement process. I would still emphasise the
three elements of the Archimedes formula: the density, weight, and size of the green, debound, and sintered parts, as well as the overall appearance of the part. These are all quality factors that are indispensable to MIM. Though it is relatively simple, this mathematical model for shrinkage is subject to constant verification and correction. The numbers presented are not static and require careful observation, minute analysis, research, and testing by practitioners.

Conclusion

I do not know whether those readers, who do not like mathematics, have been scared away, or have skimmed the above formulae to skip to the lessons we take from them, but, in truth, it is only in practice that we can truly appreciate the meaning of this mathematical model. Since the formulae for multi-material (metal, with element powder and more binders added to the recipe) combinations are more complicated, we hope that you can use the table calculation as much as possible to ease your own calculations. In future, I will discuss how to rescue feedstock that shrinks too little [sintered part dimension is too large] or too much [sintered part dimension is too small]. As well as using the compensation method for identifying unequal shrinkage after moulding, these need to be based on the mathematical model in this article. We will wait until a future issue to present these calculations.

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Industry events

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**2022**

- **EPMA Powder Metallurgy Summer School**
  - June 20–24, 2022
  - Ciudad Real, Spain
  - www.summerschool.epma.com

- **Ceramtec 2022**
  - June 21–24, 2022
  - Munich, Germany
  - www.ceramitec.com

- **Additive Manufacturing Forum Berlin 2022**
  - July 5–6, 2022
  - Berlin, Germany
  - www.am-forum.eu

- **Ceramics Expo 2022**
  - August 29–31, 2022
  - Cleveland, OH, USA
  - www.ceramicsexpousa.com

- **PMTi2022**
  - August 29–31, 2022
  - Montréal, QC, Canada
  - www.pmti2022.org

- **13th International Conference on Hot Isostatic Pressing**
  - September 11–14, 2022
  - Columbus, OH, USA
  - www.hip2022.com

- **Fraunhofer IFAM’s Sinter-based AM workshop**
  - September 14–15, 2022
  - Bremen, Germany

- **Formnext + PM South China**
  - September 14–16, 2022
  - Shenzhen, China
  - www.formnext-pm.com

- **World PM2022**
  - October 9–13, 2022
  - Lyon, France
  - www.worldpm2022.com

- **PM China 2022**
  - November 4–6, 2022
  - Shanghai, China
  - www.pmexchina.com

- **AM Ceramics 2022**
  - November 12–13, 2022
  - Dresden, Germany
  - www.am-ceramics.dkg.de

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

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**2023**

- **MIM2023**
  - February 27–March 1, 2023
  - Costa Mesa, CA, USA
  - www.mim2023.org

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**Event listings and media partners**

If you would like to see your CIM, MIM or sinter-based AM related event listed in this magazine and on our websites, please contact Kim Hayes, kimi@inovar-communications.com
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