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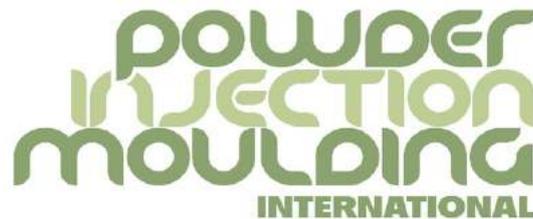
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For the MIM, CIM and sinter-based AM industries

Simulating sintering distortion: Can MIM get a boost from Binder Jetting?

As I wrote in the introduction to Desktop Metal's article on its Live Sinter simulation package, published in the September 2020 issue of *PIM International*, sintering distortion is a fact of life to which we are accustomed in the Metal Injection Moulding industry. Thankfully, through the combination of an experienced eye, the iteration of a part's design, and the use of sintering supports when needed, stable, high-volume, high-quality production is achieved.

Shortly after that issue was published, Simufact Engineering GmbH, Hamburg, Germany, part of the Manufacturing Intelligence division of Sweden's Hexagon AB, announced its own simulation package for metal Binder Jetting to enable manufacturers to predict and compensate for the distortion that sintering may have on parts. As the saying goes – you wait ages for a bus, and then two come along at once.

Two questions arose in some of the discussions that followed: how well will these packages work for metal Binder Jetting? And, assuming they are effective, can they be adapted for MIM? The industry has been waiting a long time for such a solution, and it would be a significant step forward should an effective sintering simulation package for MIM become available.

Time will tell when it comes to how useful these packages will be, but even if they take us just a part of the way to predicting how a part will behave during sintering, they will be of value. Regarding the question of whether they could also be made to work for MIM, the feedback is, so far, positive.

The rapid progress of Additive Manufacturing therefore continues to have a positive impact for MIM, with a proliferation of powder producers, more competitive powder prices, and, through sinter-based AM, the opportunity to diversify whilst leveraging existing expertise.

Nick Williams,
Managing Director & Editor



Cover image

A variety of ceramic components produced by CIM [Courtesy Expert Group CIM of the German Ceramic Society]



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In this issue

55 Ceramic Injection Moulding: Developments in production technology, materials and applications

Ceramic Injection Moulding has been a key driver in enabling the world of technical ceramics to expand from a narrow range of industrial applications to a new generation of uses in advanced engineering, high-end luxury goods, innovative medical devices, and components for electric and hybrid vehicles that are enabling society's shift to a lower-carbon future.

In this extensive review, Dr-Ing Tassilo Moritz considers recent developments in CIM production technology, materials and applications, and identifies trends that will affect the outlook for the sector. >>>



83 ElementPlus: Exploring opportunities for titanium MIM in the consumer electronics sector

Asia's burgeoning consumer electronics sector has been the driving force behind much of Metal Injection Moulding's growth over the past decade. Can this sector now help drive the MIM of titanium?

Leading Chinese Ti MIM specialist Shenzhen ElementPlus Material Technology Co., Ltd. believes that competitive powder prices, cost reductions thanks to more flexible processing, and the development of new applications with specific performance requirements, have created the perfect conditions for a breakthrough. The company's General Manager, Daomin Gu, shares her insights with *PIM International* and reports on progress to date. >>>



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93 **MIM-Master Neo: A new generation of the continuous debinding and sintering solution that changed the MIM industry**

When first introduced in the early 1990s, the MIM-Master continuous debinding and sintering furnace system from CREMER Thermoprozessanlagen GmbH, in combination with BASF SE's Catamold® feedstock, transformed MIM technology into a truly viable high-volume manufacturing process.

Today, the system has been further enhanced, and the 'next-generation' MIM-Master Neo promises even higher capacity, improved temperature homogeneity and reduced running costs. In this article, the company's Jacqueline Gruber, Hartmut Weber and Ingo Cremer tell the story of MIM-Master and outline the innovations in the new system. >>>

101 **Small-scale, complex parts with a fine surface finish: An AM solution from Incus meets the demands of MIM producers**

There can be few Metal Injection Moulding companies who are not actively exploring the potential of metal Additive Manufacturing in their business. Whilst Binder Jetting and Material Extrusion-based processes are gaining much attention, particularly for the production of larger components, things become more complex when it comes to producing the parts that fall at the smaller end of MIM's size range, where surface resolution and finish become even more critical.

In this article, Dr Gerald Mitteramskogler shares insight into Incus GmbH's Lithography-based Metal Manufacturing process with *PIM International* and explains why it is so well suited to use by MIM producers. >>>

Regular features...

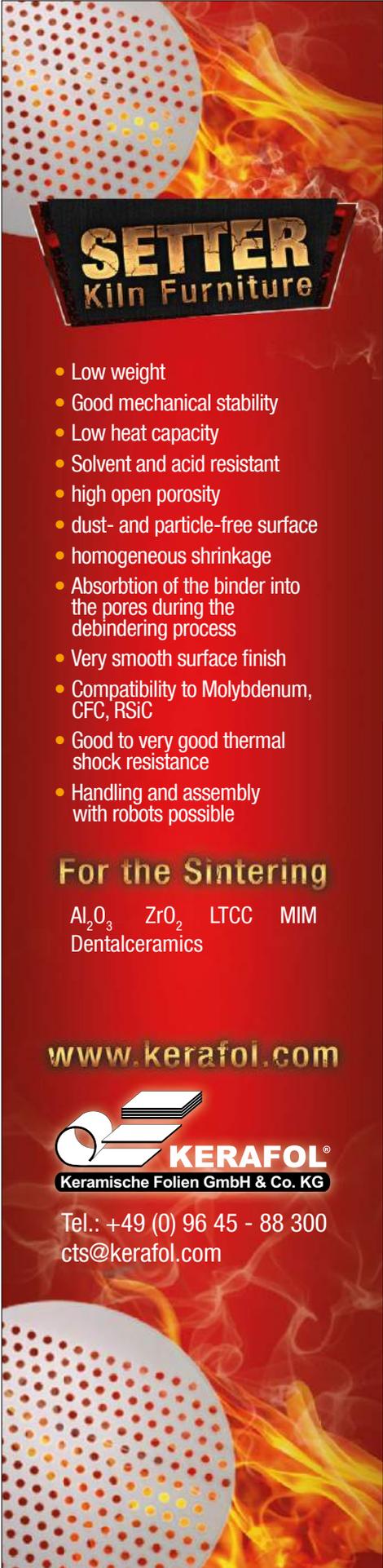
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Discover the leading suppliers of materials and equipment for MIM, CIM and sinter-based metal AM, as well as part manufacturing partners and more. >>>

110 **Events guide**

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



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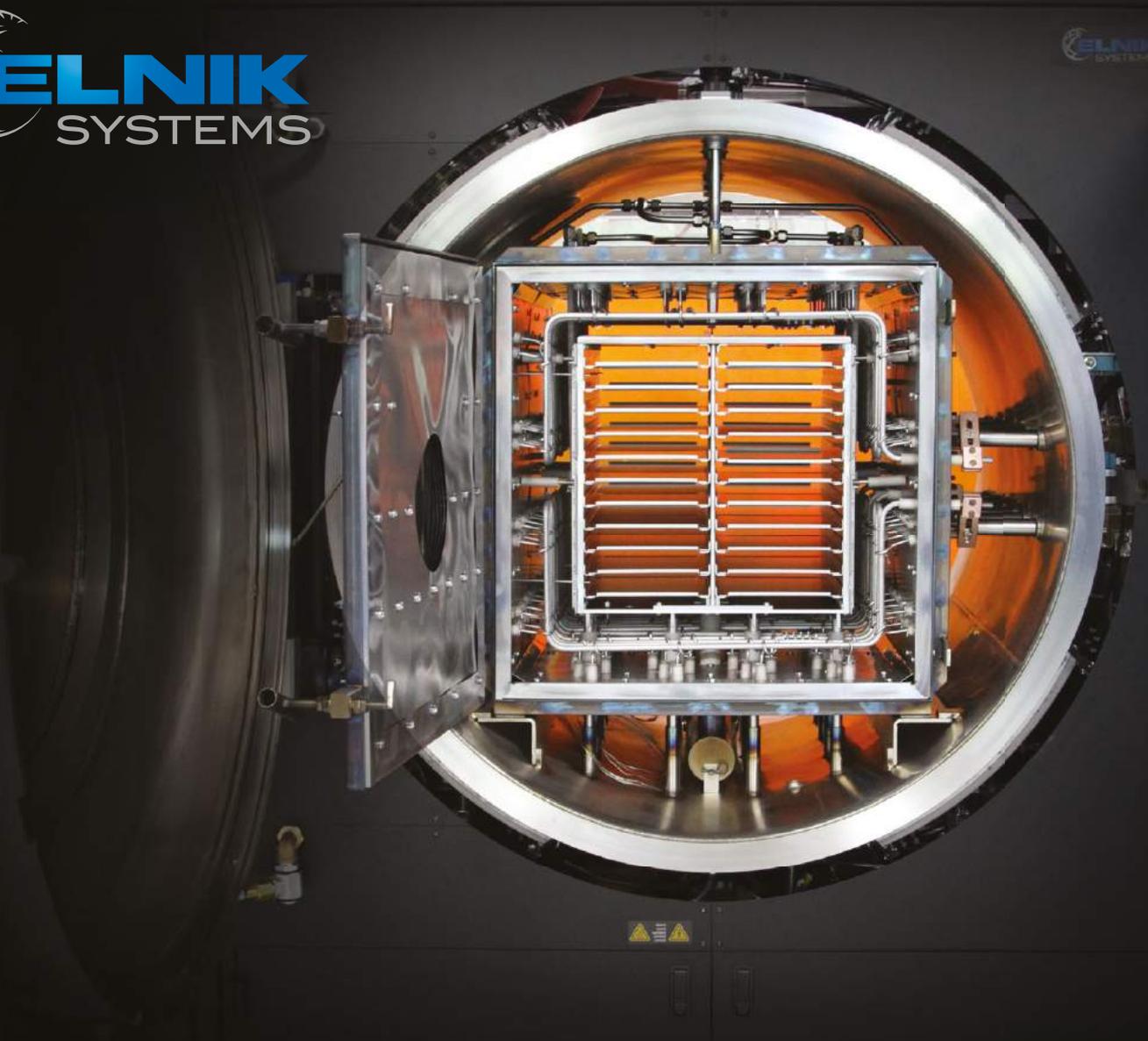
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Industry News

Epson Atmix increases water atomised powder production capacity, anticipates growing demand from AM

Epson Atmix Corporation, Aomori, Japan, an Epson Group company, has begun operations on a new production line at its Kita-Inter Plant, Hachinohe, Japan. Built with an investment of approximately JP¥1.5 billion, the new line uses the company's water atomisation process to produce what it calls 'superfine' alloy powders. The line will enable Epson Atmix, which also produces superfine alloy powders at its Head Office Plant, to increase its total production capacity to around 15,000 tons per year, about 1.5 times its current production capacity, by 2025.

The company's water atomised superfine alloy powders are classified into two main types, depending on what they are made from and how they will be used: powders for magnetic applications and powders for Metal Injection Moulding. The company's water atomisation process, in which high-pressure jets of water are used to atomise a molten metal stream generated by a high-frequency induction furnace, enables the production of micron-order particles to create alloy powders that are well-suited to MIM, with a uniform composition and characteristics. Particle size can be adjusted according to the application to increase sintered part density and strength.

The company's water atomised MIM-grade powders are well established in the global MIM industry and are used for components that have complex shapes and that require high dimensional accuracy and strength, such as parts for medical devices, automotive engine applications, consumer electronics, and office-automation equipment. The company stated that, in addition to growth from the MIM industry, demand is also expected to increase as metal Additive Manufacturing technologies become increasingly widely adopted throughout industry. Epson Atmix's lineup of MIM-grade powders includes stainless steels and low-alloy steels.

Magnetic-grade powders serve as the raw materials for electronic components such as inductors, choke coils, and reactors required to control the voltage of

high-performance mobile devices such as smartphones and laptop computers. The market for these powders is expected to expand further in the future thanks to an increase in the use of electrical components in automobiles and an increase in the number of inductors installed in hybrid and electric vehicles. Epson Atmix's magnetic-grade powders are said to contribute to the manufacture of magnetic components with low levels of magnetic loss and, as such, also contribute significantly to reducing the power consumption and size of these types of components.

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Cobra Golf launches new putter produced using HP Metal Jet, expands range of MIM wedges

Golf club manufacturer Cobra Golf, headquartered in Carlsbad, California, USA, has launched the King Supersport-35 putter, the company's first club produced using metal Binder Jetting. The development of this first additively manufactured golf club follows the company's earlier move into Metal Injection Moulding for its King MIM wedges in 2019 and the recently announced King MIM Black wedge.

Developed over the past two years in collaboration with Cobra engineers and the teams at HP and Parmatech – a leading MIM producer and launch partner in HP's Metal Jet program based in Petaluma, California, USA – the limited edition Supersport-35 putter features a fully additively manufactured 316 stainless steel body with an intricate lattice structure to optimise weight

distribution and deliver the highest-possible Moment of Inertia (MOI) in a blade shape (Fig. 1).

During the final step of the manufacturing process, the surfaces of the putter were precision milled using a Computer Numeric Controlled (CNC) machine to ensure precise shaping and detail while adding the finishing cosmetic touches (Fig. 2). The Supersport features a high MOI heel-toe weighted design for maximum stability, and a plumber neck hosel with a 35° toe hang suitable for slight arc putting strokes.

Cobra Golf explains that the additively manufactured putter represents a revolutionary advancement in the way golf clubs are designed and manufactured. The company selected HP as its partner to pioneer Additive Manufacturing in golf due to the advantages that HP's Metal Jet Binder Jetting technology, a sinter-based AM technology which shares post-processing steps and some aspects of part design and quality with MIM, presented over traditional manufacturing and other AM processes.

With its quicker processing time and greater design adaptability, the company states that its engineers were able to design, prototype, and test multiple iterations and bring the product to market much faster than has previously been possible.

Cobra and HP began working together in early 2019 and created thirty-five different design iterations over the course of eight months, showcasing the design freedom and speed of product innovation available using the HP Metal Jet machine, notes Cobra Golf.

In addition to this launch, the brands are reportedly working together on a strategic, multi-year product roadmap that leverages the design and manufacturing benefits of HP's Binder Jetting technology to deliver future golf equipment that raises performance and golfer satisfaction. Cobra plans to launch two additional products in 2021 that feature Additive Manufacturing technology.



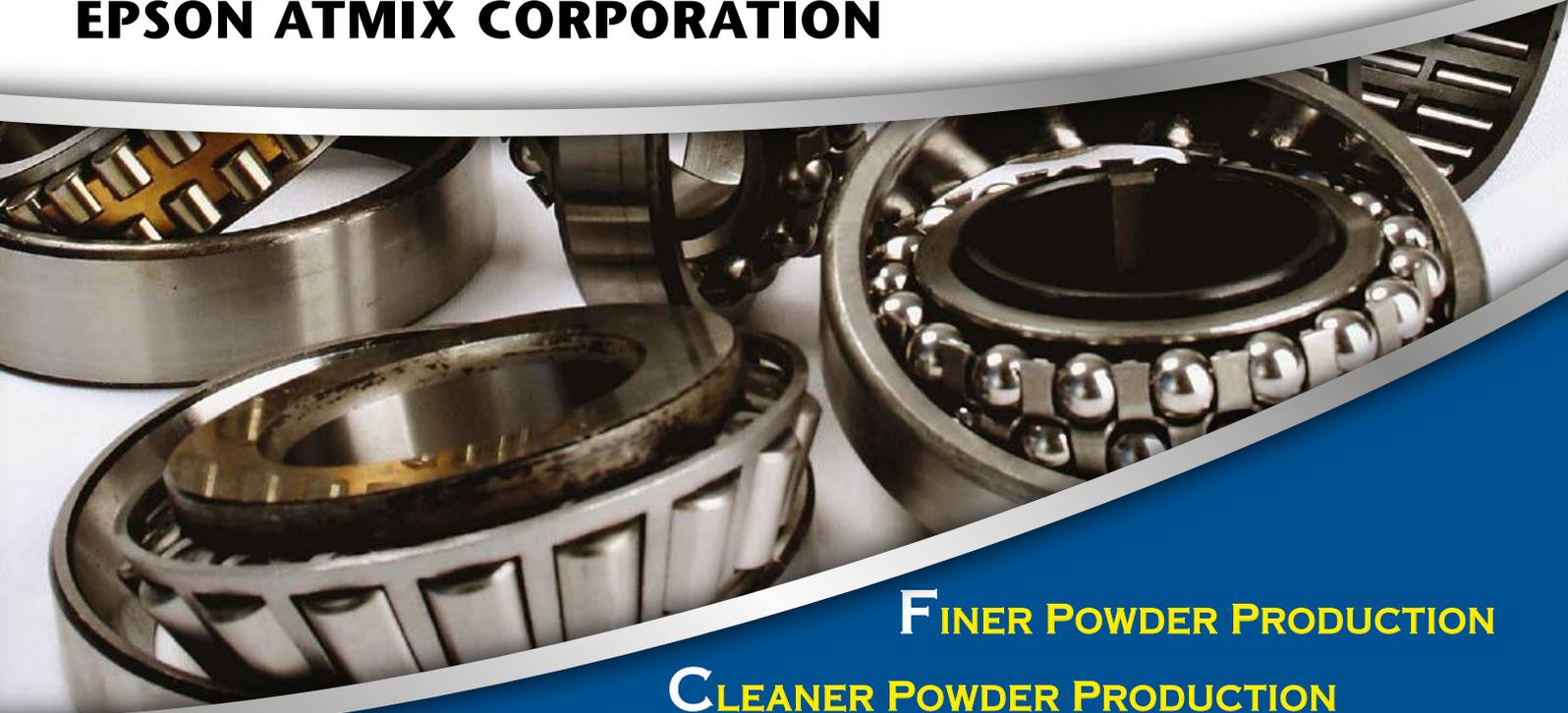
Fig. 1 The limited-edition putter features an additively manufactured 316 stainless steel body with an intricate lattice structure to optimise weight distribution and deliver the highest-possible MOI in a blade shape (Courtesy Cobra Golf)



Fig. 2 The putter's external surfaces are CNC machined to ensure precise shaping and detail while adding the finishing cosmetic touches (Courtesy Cobra Golf)



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Fig. 3 Cobra Golf has added King MIM Black wedges to its well-received King MIM line (Courtesy Cobra Golf)

"At Cobra Golf we strive to deliver high-performance products that help golfers of all levels play their best and enjoy the game," commented Jose Mirafior, vice president of Marketing, Cobra Golf. "To do that, it's critical to use the most effective manufacturing processes to design, develop, and achieve optimal results, and we've certainly done that with this new putter. To continue innovating and transforming the way equipment is manufactured, we worked with HP and Parmatech to take advantage of the benefits of Metal Jet technology."

"During the development of the King Supersport-35 Putter, we saw immediate benefits from this process, including design freedom, rapid design iteration, and high-quality parts that meet our economic demands," he added. 3D printing is accelerating design innovation, and this breakthrough putter will help usher in a new era for the sporting equipment industry at large."

"HP's 3D printing technology allows us to utilise a complex lattice structure to remove weight from the centre of the putter-head and push significant amounts of weight to the perimeter. The result is superior MOI levels and massively increased stability and forgiveness. So not only is the 3D production method more consistent but it also allows

us to design products in a new and superior way."

Uday Yadati, Global Head of HP Metal Jet, HP Inc, stated, "The power of personalisation enabled by 3D printing delivers completely reimagined consumer products and experiences. This first of its kind putter is a shining example of the disruptive design and production capabilities of HP Metal Jet 3D printing technology. Cobra's commitment to innovation and competitive excellence combined with the technical expertise and leadership from Parmatech has led to a breakthrough design win for golf fans around the world."

In addition to the additively manufactured design, the King Supersport-35 Putter, which comes in an oversized blade shape, features SIK Golf's Patented Descending Loft technology re-engineered into an aluminium face insert. The company states that this insert design strategically saves weight from the front of the putter to be repositioned heel-toe and tunes the feel to a slightly softer feel than a traditional all-steel SIK putter face. Their signature face design utilises four descending lofts (4°, 3°, 2°, 1°) to ensure the most consistent launch conditions for every putting stroke.

Bryson DeChambeau, SIK Golf partner and Cobra ambassador, reported, "I've had a lot of success over the years with my SIK putter and was really excited to work with Cobra to develop a new way to manufacture equipment and bring this new putter to market."

"HP's Metal Jet technology is an incredibly advanced production method and very exacting, which is pretty critical in golf equipment," he continued. "I think golfers of all levels will benefit from the combination of Cobra's high MOI design and SIK's Descending Loft technology."

Cobra Golf expands its MIM range with King MIM Black wedges

Cobra Golf has also reported that it is expanding its family of 'King MIM' wedges, manufactured using Metal Injection Moulding, with the addition of its King MIM Black wedges to the well-received line.

The wedge is produced from 304 stainless steel and, after sintering, robotically polished to exact specifications, eliminating the variability that can come from hand-polishing on a wheel. The end-to-end process is fully automated to deliver consistency from club to club, including on grind shapes and bounce. The King MIM black wedges have a glare-reducing Quench Polish Quench (QPQ) black finish.

The club faces and grooves are CNC-milled for maximum surface roughness to deliver the right spin profile, with milling performed in a circular pattern in order to maximise spin on softer shots where the ball won't go as deep into the grooves. The grooves are shaped uniquely to each wedge, with weaker lofts featuring wider, shallower grooves, Grooves become narrower and deeper as loft decreases.

"When we introduced MIM Wedges last year, it marked a steep change in the way wedges were manufactured," stated Tom Olsavsky, vice president of R&D for Cobra Golf. "Since then, we have received requests from better players asking for the type of black finish that is preferred on Tour."

www.cobragolf.com

www.hp.com/go/3Dprinting ■

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ExOne previews new InnoventPro metal Binder Jetting machine and binder system

The ExOne Company, North Huntingdon, Pennsylvania, USA, has released details of its InnoventPro concept, said to be the most advanced entry-level model for metal Binder Jetting. The InnoventPro will be deployed with ExOne's NanoFuse binders, a new range of inkjet-printable nanoparticle suspensions, and is scheduled for release in the second half of 2021.

According to the company, the InnoventPro will be a major upgrade of the Innovent+, which ExOne released in 2016. It will offer two new build sizes, a three and a five litre version, with build speeds topping 700 cm³/hour. The new AM machine is said to be aimed at academics, researchers, and a full spectrum of manufacturers, from machine and MIM shops to high-volume producers, who want to produce metal parts quickly, affordably and sustainably.

"Customers around the world already love the Innovent+, and based

on their feedback, we're going to give them an updated entry-level system that's bigger, faster and smarter than ever," stated John Hartner, ExOne CEO.

The InnoventPro will feature the same recirculating print head modules used on the X1 25Pro® and X1 160Pro™ metal Binder Jetting Additive Manufacturing machines, allowing users to easily scale up from R&D to high-volume production, explains the company.

The recirculating print head reportedly also enables ExOne to offer particulate binders as an option on a commercial Binder Jetting system. According to the company, its research team has been additively manufacturing a variety of nanoparticles suspended in its binders for years.

A new class of NanoFuse binders

The all-new class of NanoFuse binders, first patented in 2018 with

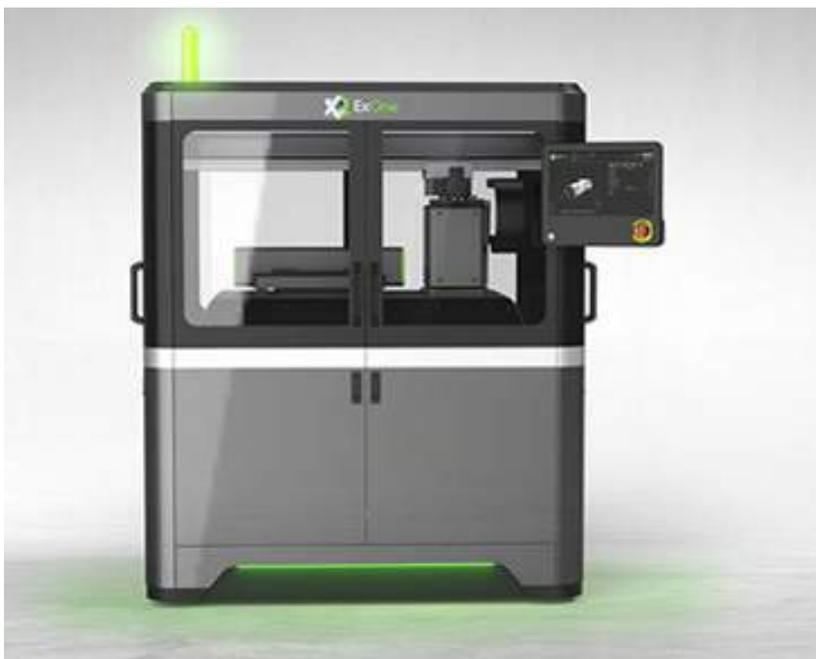
related patents pending globally, is said to advance the field of binder jet Additive Manufacturing in critical ways. The company explains that, because nanoparticles fill in the interstices between powder bed particles and can bond at lower temperatures, they enable stronger green parts. In turn, this enables the Additive Manufacturing of larger parts and finer features, delivering sharper corners and edges. These new binders are said to also improve the resolution and sinterability of high-demand metals, such as copper and aluminium.

Rick Lucas, ExOne CTO and VP, New Markets, commented, "Just as the current Innovent+ served as the proving ground for our patented Triple ACT system, which now delivers industry-leading quality in metal Binder Jetting, the InnoventPro will offer groundbreaking new features in a commercial system. Our patented approach to 3D printing particulate inks in a print bed is opening new doors in Binder Jetting."

ExOne's patented Triple ACT is a critical advanced compaction technology that, depending on the material, delivers final part density of 97+%, dimensional tolerances in the range of < 1%–2.5%, and high consistency, with part variation of just 0.3% across the powder bed.

The company explains that Triple ACT has been so effective that it has also sped up ExOne's qualification of new materials. ExOne binder jet systems now process more than twenty metal, ceramic and composite materials, with single-alloy metals making up more than half of those offerings. NanoFuse binders are expected to expand that material range and improve sintering dynamics.

www.exone.com ■



ExOne's InnoventPro is a new entry-level Binder Jetting system for additively manufacturing metals, ceramics and composites (Courtesy The ExOne Company)

Discover our new Buyer's guide...

Find new suppliers of materials, production equipment and finished MIM or sinter-based AM parts on pages 108–109

The BINDER for thermal debinding systems, capable of being recycled up to 10 times!

- Just regrind the sprue, runner and unwanted green parts then reuse!
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- No change in the shrinkage ratio or physical properties!
- No change in mouldability!
- No need to modify debinding and sintering setup!

Binder system design

Characteristics required for Binder

- **High flowability at molding temperature**
Binder design considering the viscosity at around the molding temperature.
- **High expansion property in the mold during injection moulding**
Wide moulding condition range because of the Barus Effect. (Fig.1 and 2)
- **High thermal decomposition property in the de-binding process**
There is no effect on the sinter quality, because there is no residue after de-binding. (Fig.3)

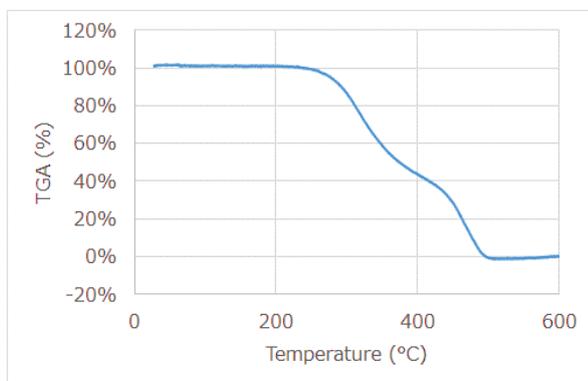


Fig.3 TGA Curve of Binder

※All components are vaporized at around 500°C.

The flow amount F , when the load S is applied to the thermoplastic fluid, is given as following equation.

$$F = aS^n$$

Here, a is the flow characteristic at load=1, n is Barus effect.

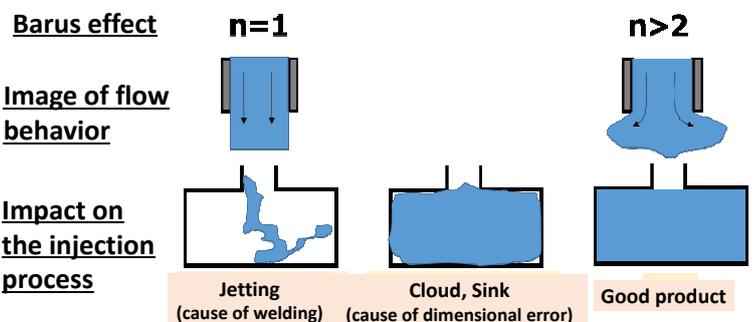


Fig.1 Schematic of the relationship between n value and flow characteristic

※Since larger n value, material expands in the mould, dense green part is obtained.

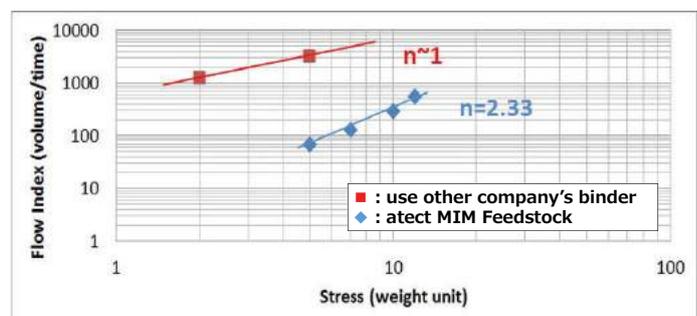


Fig.2 Flow characteristic compared with pellets using the other company's binder

※With our binder, it is possible to obtain precise green part because material easily expands in the mould.

Euro PM2020 Virtual Congress brings PM community together online

The European Powder Metallurgy Association (EPMA) held its Euro PM2020 Virtual Congress from October 5–7, 2020. The Virtual Congress, the first online edition of the EPMA's annual Powder Metallurgy Congress, included over 160 oral presentations, with interactive Q&A discussions with the authors following each technical session.

The technical programme represented all areas of Powder Metallurgy, including Additive Manufacturing, functional materials, hard materials and diamond tools, Hot Isostatic Pressing, Metal Injection Moulding, new materials, processes and applications, and conventional press and sinter PM.

"Moving to a digital platform was a big challenge, but I am delighted with the event we were able to deliver.

We had such a strong technical programme this year that it would have been truly unfair to the speakers not to have the opportunity to present their work," stated Lionel Aboussouan, EPMA Executive Director.

Ralf Carlström, EPMA president, opened the Plenary Presentations with an overview of the status and trends in the European PM industry. This was followed by Jean-Marie Reveille of automotive benchmarking company A2MAC1 who presented on current and new opportunities for PM components in new mobility.

"Our members are always enthusiastic about the latest research in PM and I think we found a great method of delivering it to them," concluded Aboussouan.

www.epma.com ■

APP completes expansion

Advanced Powder Products, Inc. (APP), Philipsburg, Pennsylvania, USA, a company specialising in MIM and metal Additive Manufacturing, has announced the completion of a 2,300 m² expansion of its manufacturing facility.

With the MIM industry said to be growing at a rate of 5–7%, APP explains that the expansion will allow the company to better serve its customers and facilitate its continued growth, adding capacity for subsequent years. The new facility houses a state-of-the-art quality lab, increased processing capabilities, automation development facilities and a research and development centre. The company's growth plans include the hiring of skilled professionals, engineers, and technicians, as well as entry-level manufacturing support.

www.advancedpowderproducts.com ■

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Blue Power and Amazemet develop compact ultrasonic atomiser

Blue Power Casting Systems GmbH, Walzbachtal, Germany, in cooperation with Amazemet Sp. z o.o., a Warsaw University of Technology spin-off company, has developed a compact ultrasonic atomisation unit for R&D purposes and small powder batch production. Dr Fischer-Bühner, Head of R&D at Blue Power, stated that the atomiser unit enables users to produce small batches of high quality, spherical powder for the same target application as gas atomised powder at an affordable price and without complex infrastructure.

The ultrasonic atomiser solution features a crucible-based induction heating system which allows the melting temperature to be precisely controlled, thereby preventing the loss of alloy ingredients such as zinc and chromium through evaporation.

The melting can either take place under vacuum or in a controllable atmosphere. The powerful medium-frequency induction generator produces excellent stirring/mixing effect, improving the quality of the alloying. "A crucible-based induction heating system has many economic benefits over plasma-assisted ultrasonic atomisation," commented Mateusz Ostrysz, co-founder of Amazemet.

The loss of alloy ingredients through evaporation is prevented without the need for any sophisticated and expensive filtration systems, state the developers. The system is not restricted to just pre-alloyed wire and bar; the feedstock can be any shape. This means that users can avoid the time and effort needed to produce complex and expensive wire, no longer needing the associated

infrastructure such as continuous casting machines and drawing benches.

Very small batch sizes, of around 100 g or less, are reported to be both technically and financially viable, while larger production capacity of up to several kg (bronze) per hour is possible. An increased powder yield is made possible due to operating at a higher frequency (up to 80 kHz). For example, bronze particle sizes in the range of D50=40–60 µm can be easily achieved, with further improvements on the horizon.

The ultrasonic process is said to offer the flexibility users require in terms of both inputs and outputs. The plant can reportedly handle almost any non-ferrous metal in any shape with a melting temperature less than 1300°C, with the company also developing an 1800°C version. No calibration is needed; pre-installed programs cover the basic materials and alloys.

www.bluepower-casting.com
www.amazemet.com ■

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Call for Speakers issued for Ceramics Expo 2021 Conference

Smart Shows Tarsys Ltd, the organiser of Ceramics Expo, has issued a Call for Speakers for the Ceramics Expo 2021 conference, which is scheduled to take place in Cleveland, Ohio, USA, from May 3–5, 2021. The free-to-attend conference runs concurrently to the exhibition and brings together industry leaders to share their technical expertise in ceramics and provide real-world case studies, new technologies and materials, along with information on industry trends.

The 2021 conference will continue with the theme of enabling “a clean, efficient and electrified future.” This approach will explore Ceramic matrix composites (CMCs), catalysts and filtration, technical and industrial coatings, metallisation of ceramics and ceramic coatings on metal alloys amongst many other key topics, explains the organiser.

Abstracts are welcomed on the following topics:

Industry trends

- Costs and industry financial issues, such as economic forecasting, material availability, etc.
- Workforce development
- Overviews of technical hurdles that need to be overcome in future markets
- Raw and precious materials acquisition
- Industrialisation

Applications

- Ceramic matrix composites
- Mobility
- Sensors

- Energy storage and harvesting
- Composite and ceramic materials: synthesis and characterisation, structure and design
- Filtration
- Ceramic coating
- Machining of CMCs
- Electronic packaging
- Coatings (Thermal barriers)
- Catalysts

Materials properties

- Electric
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- Optical
- Wear and corrosion

Manufacturing

Process improvement (lead time and cost), innovation, and best practice of:

- Ceramic AM
- Improvement of forming processes: Ceramic Injection Moulding, slip casting, pressing, tape casting, Hot Isostatic Pressing, etc.
- Improvements in resin formulation, slurries, additives, rheology
- Coatings
- Improvements in debinding and sintering processes
- (Precision) finishing
- Testing and analysis
- Applications of Big Data in manufacturing processes

Abstracts should be submitted by January 17, 2021. Further information and submission guidelines are available via the event website.

www.ceramicsexpousa.com ■

Rapidia launches new rapid cooling furnace



Rapidia's new rapid cool sintering furnace enables an entire sintering cycle to be completed in about twenty hours (Courtesy Rapidia Inc)

Sinter-based Additive Manufacturing technology developer Rapidia Inc, based in Vancouver, British Columbia, Canada, has launched a new rapid cooling sintering furnace. The new furnace was developed while the company was in the process of improving the insulation in its existing sintering furnaces, to reduce heat losses and limit skin temperature in AM parts. During this process, the company explains that the detrimental side effect of a lengthy cool down time became apparent. The rapid cooling furnace is said to mitigate this effect.

Rapidia's new furnace is available in the same compact size as the company's earlier furnace designs, sized to fit through an office door and occupy a minimal footprint. In the new model, the need to install a vent to the building exterior has been eliminated by the addition of a high-end activated carbon filter, while the power requirements remain unchanged.

Using the rapid cooling furnace, the entire sintering cycle can reportedly be completed in about twenty hours. As parts produced using Rapidia's Material Extrusion (MEX)-based AM process, which uses water as the binder, do not require a debinding step, it is said that parts can be built and sintered to completion in under twenty-four hours.

www.rapidia.com ■

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South China MIM & AM summit highlights new business opportunities for part manufacturers

The second South China MIM & Additive Manufacturing Technology and Application Summit took place on November 26, 2020, at the Lotus Villa Hotel in Chang'an, Dongguan, China. Co-organised by China Powder Metallurgy Alliance (CPMA), Guangzhou Guangya Messe Frankfurt Co Ltd and Uniris Exhibition Shanghai Co Ltd, the summit welcomed over 200 attendees and highlighted the latest developments within the Metal Injection Moulding and Additive Manufacturing sectors.

Industry experts and academic speakers shared their market insights within the automotive, medical, consumer electronics, and communications industries and also unveiled the latest market intelligence and development opportunities. The summit was moderated and chaired by Professor Li Yimin of the Powder Metallurgy Research Institute of Central South University and Deng Zhongyong, Dean of the Central Research Institute of Shanghai Fuchi High-Tech Co Ltd.

Zhang Zhiheng, Secretary General of Professional Committee of CPMA, Professor Yan Biao, Chairman of the Shanghai Powder Metallurgy Industry Association, and Louis Leung, Deputy General Manager of Guangzhou Guangya Messe Frankfurt Co Ltd delivered their opening remarks during the summit's opening ceremony and stated that the convergence of AM and MIM technologies is presenting new business opportunities for part manufacturers.

In addition, twelve experts representing the National Tungsten Engineering and Technology Research Center, Shanghai Materials Research Institute, University of Science and Technology Beijing, Tongji University, Southern Medical University, Southern University of Science and Technology, Guangdong University of Technology presented their research and perspectives on AM and MIM, as well as an analysis of industry trends and market prospects.

Approaching the end of the summit, Dr Yaohong Qiu, Chief Lecturer and founder of the You Need Technology Consultation Company, hosted the Summit Salon, which was the final session of the event that included opportunities for networking and a Q&A session for participants and speakers.

The organisers stated that they view the summit as a 'warm-up' event for the Formnext + PM South China trade show, which will take place for the first time on September 9-11, 2021, in Shenzhen, China. The summit advocated the importance and advantages of the new fair to the industry and featured the expected highlights of the upcoming exhibition.

www.formnext-pm.com ■

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Linde launches gas for optimal sintering in the Desktop Metal Studio System

Linde, a global industrial gas specialist headquartered in Guildford, Surrey, UK, has launched ADDvance® Sinter250, a new gas mixture designed to deliver optimal atmospheric conditions in sintering furnaces as part of Desktop Metal's sinter-based Additive Manufacturing process. The argon/hydrogen gas mixture has reportedly been developed for Desktop Metal's European customers, for use with the company's Studio System™.

Linde states that it will also supply customised installation kits to simplify the implementation of the Studio System, allowing for faster start times, as well as consultancy

services to advise on gas supply options and best practice for cylinder storage.

According to Linde, the tailored argon/hydrogen mix of ADDvance Sinter250 is for use on parts made from stainless steel powders, but the company states that it will also supply a pure argon 5.0 gas for the manufacture of parts made from low-alloy steel and tool steel powders.

"Linde has long been a pioneer in the development of innovative gas mixtures to optimise manufacturing processes," stated Pierre Forêt, senior expert Additive Manufacturing, Linde. "In this rapidly developing world of Additive Manufacturing, we are delighted to be collaborating with an innovator in the space such as Desktop Metal to supply this gas mixture to their customers."

Arjun Aggarwal, VP of Business Development & Product, Desktop Metal, commented, "Linde has



Linde has launched a new gas mixture to optimise sintering in Desktop Metal's Studio System (Courtesy Linde/Desktop Metal)

developed a standard gas offering optimised for Studio System and is able to offer this streamlined solution to our European Desktop Metal customers. This enables us to expand our horizons and bring added value to our business."

www.linde.com

www.desktopmetal.com ■

Thermal Process Equipment for PIM Manufacturing

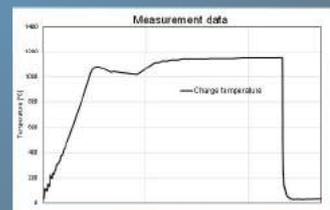


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www.cremer-polyfour.de

Steinbach invests in Lithoz's CeraFab System S65 to develop high-performance ceramics

Steinbach AG, Detmold, Germany, reports that it has expanded its machine park by investing in an additional CeraFab System S65 from Lithoz GmbH, Vienna, Austria.

Steinbach offers prototyping in series quality as well as series production for a wide range of applications and industries, including medical technology, high-temperature applications, and the electrical, automotive and aerospace industries.

With the addition of the CeraFab System S65 and the company's investment in the latest generation

of industrial Additive Manufacturing machines for high-performance ceramics, as well as furnaces, Steinbach states that it is meeting the growing demand for additively manufactured high-performance ceramic components.

The CeraFab System S65 can be expanded to up to four production units to meet the needs of industrial series production. In combination with optimised process parameters, a significant increase in productivity is achieved, notes Steinbach.

"We continue to trust in the cooperation with Lithoz and their



Steinbach has invested in a CeraFab System S65 from Lithoz (Courtesy Lithoz GmbH)

CeraFab 3D printers because we are convinced of the outstanding quality and also find competent and fast support in our daily work," commented Volker Sämman, Business Unit Manager of Steinbach AG.

www.steinbach-ag.de

www.lithoz.com ■

Zimmer Group converts production to sustainable carbon-neutral system

The Zimmer Group, Rheinau, Germany, reports that it marked its 40th anniversary this year with the conversion of its production to a sustainable CO₂-neutral system. The company's portfolio of manufacturing capabilities includes a Metal Injection Moulding operation for in-house and third-party production.

According to the group, one million kilowatt-hours of green electricity are generated annually from the Süwag hydroelectric power station in Willstätt, 15 km away. Now, the Zimmer Group states that it generates approximately the same amount of CO₂-neutral electricity. Several photovoltaic systems are already installed on the company roofs in Freistett, and the group plans for another photovoltaic system to be put into operation on its newly built production hall.

"Consuming electricity where it is generated in an environmentally friendly manner directly on site is an essential component of our environmental strategy," stated Günther

Zimmer, Managing Director, Zimmer Group.

"The Zimmer Group is thus becoming another piece of greener and more regional infrastructure," he continued. "All in all, these measures will save a total of 5,595 tonnes of CO₂ per year, which corresponds to about fourteen fully-fueled jumbo jets. The climate-neutral eco gas saves a further 295 t CO₂."

The Zimmer Group explained that it is also taking steps in the area of electric mobility to minimise CO₂ emissions. At both company sites in Freistett, a total of sixteen charging points will be set up in the car parks to charge electric vehicles during working hours; the company's vehicle fleet is also being successively converted to electric vehicles and plug-in hybrids.

Michael Fischer, the Zimmer Group's Environmental and Energy Management Officer, explained that the group is committed to the continuous optimisation of environmental protection services,

and auditing according to ISO 50001 underlines its successful measures.

"More than 100 current measuring points were installed for consumption monitoring and analysis," he stated. "This enabled us to identify many more potential savings and to derive measures from them." One further example is the use of heat pumps for air conditioning its buildings and cooling its machines, the optimisation of the company's compressed air network, and the switch to LED lighting.

As part of the Zimmer Group's future plans, it also wants to sensitise its employees to environmental protection and energy. For this reason, five trainees were recently qualified by the Southern Upper Rhine Energy Chamber of Commerce and Industry and advised by Michael Fischer.

As part of the 'Energy Scout' project, these trainees looked for new ways to save energy and identified them in the compressed air guns that the company needs for production, among other things. The necessary nozzles are now being developed in-house to enable the compressed air guns to consume considerably less energy.

www.zimmer-group.com ■

Arburg launches additional functions for its Allrounder 270 S compact machine

Arburg GmbH + Co KG, Lossburg, Germany, has launched additional functions for its hydraulic Allrounder 270 S compact injection moulding machine in order to expand the range of applications.

The machine can now be configured online via the arburgXworld customer portal and ordered directly with short delivery times. It also now offers more modular configuration options and functionality.

Additional functions and features

The company explains that its Allrounder 270 S compact with 350 kN of clamping force and a size 100 injection unit is now available with a parting line unit. By repositioning the injection unit, it can also be used to vertically inject in the mould

parting line, enabling a wider range of moulds and processes.

In order to work with a wider range of materials, highly wear-resistant chrome nitride-coated cylinder modules are optionally available states Arburg. For automated applications, the Allrounder 270 S compact can also be equipped with an Integralpicker V. In addition, machines in the field can be retrofitted with a robot interface if required.

According to the company, the compact machine stands out for its minimal footprint, a control cabinet integrated into the machine base and energy-saving servo hydraulics [ASH]. The Selogica control system with its range of functions is said to ensure reliable quality even for demanding cycles.

The hole patterns in the mounting platens take into account all standard requirements for mould technology in this size class, optionally for Europe or the USA. To comply with current safety standards, the socket combinations of the machine are equipped with RCD protection as standard.

Direct distribution to reduce cost and delivery times

With the hydraulic Allrounder 270 S compact now being directly available online, Arburg explains that in order to benefit from this new option, customers must initially register free of charge on the customer portal via the company website and then activate the configuration app. With this tool, standardised machines can be individually configured by adding defined options and then ordered with fixed conditions.

www.arburg.com ■

Sandvik Additive Manufacturing joins GE Additive's binder jet beta partner programme

GE Additive reports that Sandvik Additive Manufacturing, a division of Sandvik AB, headquartered in Stockholm, Sweden, has joined its binder jet beta partner programme. Sandvik has one of the widest alloy programmes for Additive Manufacturing, marketed under the Osprey® brand.

Sandvik will work closely with GE Additive to become a certified powder supplier for a range of Osprey alloys that complement GE Additive and AP&C's own materials portfolio, and will reportedly also use GE Additive's H2 Binder Jet beta machine to support its internal and external customers.

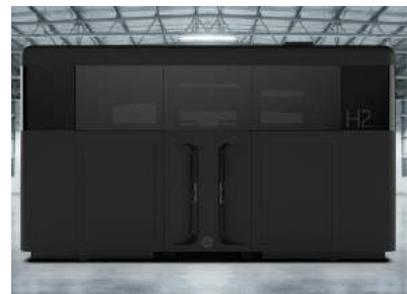
GE Additive's binder jet beta partner programme hopes to leverage its strength in industrialising Additive Manufacturing technology with strong technical and innovative partners to rapidly grow its Binder Jetting technology. The first phase is said

to involve developing the beta H2 system into pilot lines, and eventually into a commercially-available factory solution in 2021.

"Our approach to binder jet is making additive mass production a reality in every industry," stated Jacob Brunsberg, Binder Jet Product Line Leader, GE Additive. "And while it would be relatively easier to launch individual machines, we continue to hear from customers, especially in the automotive industry, that they need a complete solution that can scale."

Brunberg continued, "Attracting partners like Sandvik – with know-how in industrialising innovation, deep materials knowledge, and a shared vision for the potential for additive technology – remains a cornerstone of our binder jet commercialisation strategy."

Kristian Egeberg, president of Sandvik Additive Manufacturing,



GE Additive's H2 Binder Jet beta machine, which will continue to be developed as part of the first phase of the binder jet beta partner programme (Courtesy GE Additive)

commented, "Sandvik is a leading expert in gas-atomised Additive Manufacturing powders, as well as in optimising the materials to customers' specific print processes and applications. The materials collaboration with GE Additive offers great opportunities to qualify our wide range of Osprey metal powders for their new binder jet platform, to enhance end-customer productivity and product performance."

www.ge.com/additive
www.additive.sandvik ■

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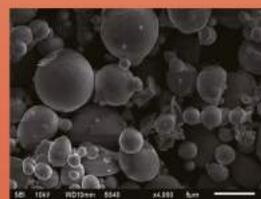
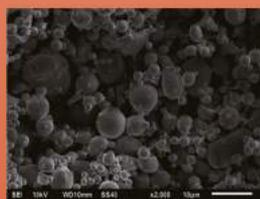
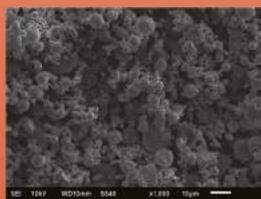
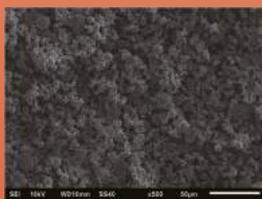
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17-4PH	4.7	0.34	7.7
304L	4.8	0.34	7.8
HK30	4.7	0.34	7.7
4J29	4.9	0.34	7.95
F75	5.0	0.34	8.1



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Simufact introduces new module to compensate for sintering distortion in Binder Jetting



Three phases of automated optimisation show compensation for distortion using the metal Binder Jetting module in Simufact Additive. The results show the deviation between the simulated part and its initial CAD geometry – blue/red = bad; green = good (Courtesy Simufact)

Simufact Engineering GmbH, Hamburg, Germany, part of the Manufacturing Intelligence division of Sweden's Hexagon AB, has introduced its metal Binder Jetting (BJT) module for its Simufact Additive simulation software, which enables manufacturers to predict and prevent the distortion that sintering processes can have on parts during design.

The company states that its new simulation tool marks a significant step forward for Additive Manufacturing because it helps manufacturers achieve the high quality they require while exploiting the unique benefits BJT offers for volume production. It is understood that there is also interest in applying this technology to support the sintering distortion simulation of parts produced by Metal Injection Moulding.

Simufact explains that one key challenge in metal Binder Jetting has been the prediction of changes during the sintering process. A part can shrink as much as 35% during

sintering, and the simple shrinkage models used for other processes cannot predict this distortion for AM. Until now, costly physical trials were required to perfect the Additive Manufacturing of each part, preventing many manufacturers from realising the low cost and flexibility BJT offers, notes the company.

The new simulation tool, which was made available to existing Simufact Additive customers in August 2020, extends its capabilities for BJT processes. Manufacturers can predict the shrinkage caused by factors such as the thermal strain, friction, and gravity during sintering without specialist simulation knowledge.

By compensating for these changes, parts can be additively manufactured as they are designed, and production teams can significantly reduce the proportion of parts that must be scrapped or re-processed. Sintering-induced mechanical stress is also predicted before the build, indicating where

defects might occur. Manufacturers can use this information to make changes earlier in their product development and reduce the need for costly redesign.

Designed for busy manufacturing professionals, the simulation tool can automate the model setup, preparing the CAD or CAE file for manufacturing simulation, and simulations can also be automated through Python scripts. To validate the sintering compensation and increase confidence in quality, the optimised geometry from the tool can be immediately compared to both the initial design (CAD) geometry and a metrology scan of a manufactured part within the user interface.

"We are pleased to introduce the first solution for simulating the metal Binder Jetting sintering process to the market so that manufacturers can take advantage of this important new method," commented Dr Gabriel McBain, Senior Director Product Management, Simufact & FTI.

"We know customers see metal Binder Jetting as a pivotal technology for manufacturing, particularly where there's a need to produce intricate parts at high volumes like the automotive industry. This development was only possible through close collaboration between our manufacturing and printer equipment partners and our highly experienced research & development department," concluded McBain.

www.simufact.com
www.hexagonmi.com ■

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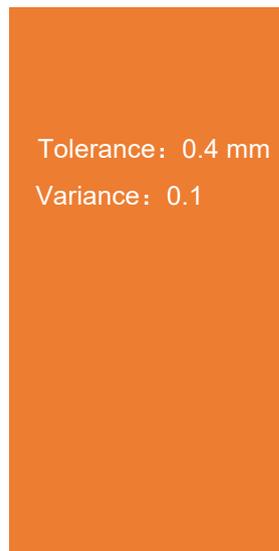


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Dr John Johnson to lead Operations and Technology at MIM powder specialists Ultra Fine and Novamet

Ultra Fine Specialty Products, LLC, (Ultra Fine) an affiliate of Novamet Specialty Products Corporation, Inc, Lebanon, Tennessee, USA, has announced the appointment of Dr John Johnson, PhD, as vice president, Operations and Technology of both companies. In his new position, he will be responsible for the manufacturing and technical facilities located in Tennessee and Rhode Island, USA.

Johnson is said to have an extensive background in particulate materials processing of metals and ceramics, including compositions based on tungsten, molybdenum, titanium, iron, nickel, copper, silica, alumina, silicon nitride and aluminium nitride.

His research has encompassed all methods of powder production and consolidation, especially Powder Injection Moulding, extrusion, die compaction, isostatic pressing, and freeform fabrication, and he is said to have helped pioneer the rapid prototyping of iron-copper mould inserts. Johnson has published over a hundred papers in the areas of Powder Metallurgy, ceramics and PIM. He is the recipient of numerous awards, and was granted APMI Fellow status in 2019.

Ultra Fine was purchased on June 30, 2020, from Carpenter Technology by a group of investors, including Johnson, all of whom are affiliated with Novamet Specialty Products. According to the company, its atom-

ising facility produces the highest quality metal powders of their kind globally, in the finest range of sizes available through gas atomisation.

Novamet Specialty Products Corporation was formed in 1976 to apply technology to the development of nickel-base powders and technologies into different morphologies, shapes, and sizes for various industrial uses, focusing on nickel powders produced by its then-parent, Inco.

The company was acquired by investors in 2010 and, after nearly forty years in Bergen County, New Jersey, USA, moved its headquarters and manufacturing facilities to Lebanon, Tennessee. Novamet currently processes and distributes various metal powders and coated products for the Metal Injection Moulding, aerospace, automotive, coatings and electronic materials markets.

www.novametcorp.com ■

Markforged names new president and Chief Executive Officer

Markforged, Watertown, Massachusetts, USA, has announced the promotion of Shai Terem to president & Chief Executive Officer. Gregory Mark, founder of Markforged, has now transitioned to the role of chairman. The leadership announcements are the results of a planned succession and are said to be designed to position the company for continued success in the next phase of its growth.

As CEO, Terem will lead the development and execution of short- and long-term strategies and day-to-day operations, with the aim of positioning Markforged to continue delivering value to its key stakeholders as the company continues to scale.

Since joining Markforged in December 2019 as president and Chief Operating Officer, Terem has reorganised the company to incorporate a channel-first approach while building a strong infrastructure for rapid, efficient and scalable growth. Previously, he served as president

of the Americas region at Kornit Digital, a global specialist in 2D digital printing for textiles, and held various product marketing, finance, and operations roles within the AM company Stratasys.

"I have been fortunate to spend the majority of my career in this industry – experience that gives me profound appreciation for the immense value that Markforged brings to organisations around the world," stated Terem. "Our tools are designed to allow manufacturers to go from design to a functional part with unmatched efficiency to truly optimise the supply chain. It is an honour to take the helm of such a pioneering company, and I'm eager to play my part in our mission to reinvent manufacturing."

Gregory Mark stated, "Leading Markforged for the past seven years as Chief Executive Officer has been an amazing journey, and I'm incredibly proud of what we've built. Before

Markforged, access to strong 3D printed parts was limited to those who could afford million-dollar machines."

"Today, we have parts flying in space, and on commercial and military jets; we have hundreds of thousands of parts used by frontline workers to fight COVID," he continued. "All are printed on a platform that is robust enough for end-use aerospace, and affordable to high schools and colleges. We have democratised metal and carbon fibre 3D printing, and we're just getting started."

"We believe Shai will continue this progression and grow into more factories, schools, and design shops around the world," he added. "With his operator chops and considerable Additive Manufacturing experience, Shai has the right combination of skills to continue our rapid growth."

In his new role as chairman, Mark will focus on promoting adoption of the company's Additive Manufacturing platform among engineers, designers and manufacturing professionals all over the world.

www.markforged.com ■

Tritone announces installations of its Dominant sinter-based metal AM machines

Tritone Technologies, a metal AM technology company based in Rosh Haayin, Israel, has installed its first Tritone® Dominant beta AM machine at Israel-based Runout, a provider of CNC machining and milling for industrial, high-tech and aerospace applications. A further beta installation of Tritone Dominant is planned before the end of 2020 at a customer site in Germany.

Tritone Dominant enables the industrial-scale production of high-quality metal parts and is based on Tritone's patent-pending MoldJet® technology, a sinter-based process designed for producing large quantities of high-density parts with complex geometries, explains the company. Since its introduction at Formnext 2019, Frankfurt, Germany, Tritone states that it has improved the Dominant AM machine and increased its set of available alloys to address the rigorous requirements of industrial applications. "Tritone Dominant is an important addition to our operations," stated Arnon Langevitz, co-CEO and founder of Runout. "With its high-quality AM capabilities, we are better equipped to serve our customers in various applications. We are able to produce very accurate, repeatable parts in short timelines at a reduced cost."

"The Dominant system opens new opportunities of re-engineering and designs for our customers, which were not feasible before," Langevitz continued. "We can now support them with weight reduction, producing a single merged part instead of separate pieces before, and complex internal passages."

Omer Sagi, VP Products and Business Development at Tritone, commented, "We are very excited to see Runout utilising the Tritone Dominant. Following the unveiling of Dominant last year, we have made tremendous progress in adjusting it to the needs of serial production, from cut design to end parts."

"We continue to add more options of raw materials to address the market demands. The Runout installation marks a significant milestone for Tritone. We are ready to support them in making the best use of the system and looking forward to additional deployments," Sagi concluded.

www.tritoneam.com ■



A Tritone Dominant beta metal AM machine has been installed at Runout for producing industrial metal AM parts (Courtesy Tritone Technologies)



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www.loemi.com

Ricoh develops Binder Jetting process for aluminium part production

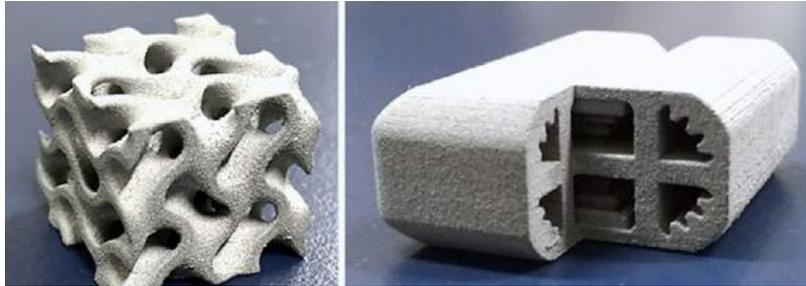


Fig. 1 Binder jet sample parts incorporating internal channels (Courtesy Ricoh)

With metal Binder Jetting (BJT) systems now offering the potential for the high-volume, cost-effective Additive Manufacturing of complex parts, there is a growing demand to broaden the range of material options available. Aluminium is one such metal that could offer the potential to produce a variety of new parts; however, the metal can be difficult to process in the sintering stage.

To alleviate this problem, a team of researchers at Ricoh Company Ltd, based in Kanagawa, Japan, has developed a unique binder material that, when combined with a suitable debind and sinter stage, offers the potential to use typical aluminium powders in the Binder Jetting process. Furthermore, the use of a liquid immersion technique developed at Ricoh for removing excess powder is said to make it possible

to form complex internal channels during the process – an option the company says is not possible with conventional processes (Fig. 1).

For the development of this new binder system, the team used an AlSi alloy powder with an average particle size of 35 μm , coated with what is described as a resin. The main objective of the resin coating, explains Ricoh, is to allow bonding through a mutual interaction with the binder liquid, as well as reducing the risk of explosion. The binder liquid used incorporates an organic solvent and an additive to ensure the cross-linking of the resin-coated powder particles.

Ricoh used a prototype Binder Jetting machine, developed in-house, to create a powder layer thickness of 84 μm with a binder liquid drop resolution of 300 x 300 dpi. The resulting green body

was said to be resistant to specific solvents due to the cross-linking. Immersing the parts in a solvent for a set time therefore enables the efficient removal of excess powder, particularly from small internal channels.

Following a solvent drying stage, the parts undergo a liquid-phase sintering operation. A target liquid phase amount of approximately 20–30% is required, with the parts maintaining a temperature appropriate for elution of the liquid phase amount for between two and five hours.

The researchers reported that tensile strength testing, thermal conductivity testing, cross-section structure observation, and X-ray CT internal observation were performed on the resulting sintered parts. The tensile strength and stretch values of the test sample seen in Fig. 2 were reported to be 100 MPa, equivalent to that of a typical pure aluminium material. Using a xenon flash analyser, thermal conductivity was determined to be 188 W/mK, equivalent to AlSi die-cast products.

An X-ray CT image of a sintered block, measuring roughly 15 mm per side, is shown in Fig. 3. The sample's relative density reached 98.4%, and it was confirmed that sintering was accomplished well, with no large pores. The results of microstructural observations (Fig. 4, overleaf) found that grain sizes were approximately 50 μm , equivalent to a typical cast structure.

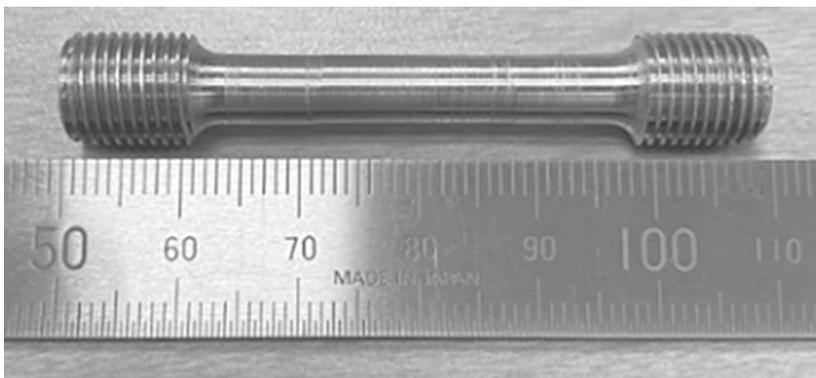


Fig. 2 The tension test specimen, for which mechanical processing was performed on a resulting sintered body (Courtesy Ricoh)

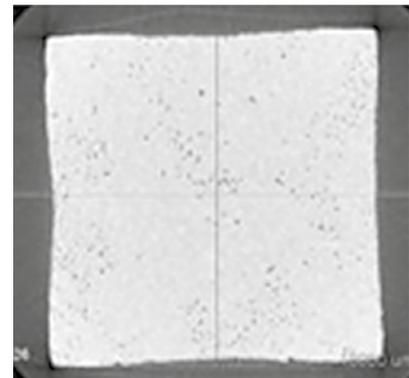
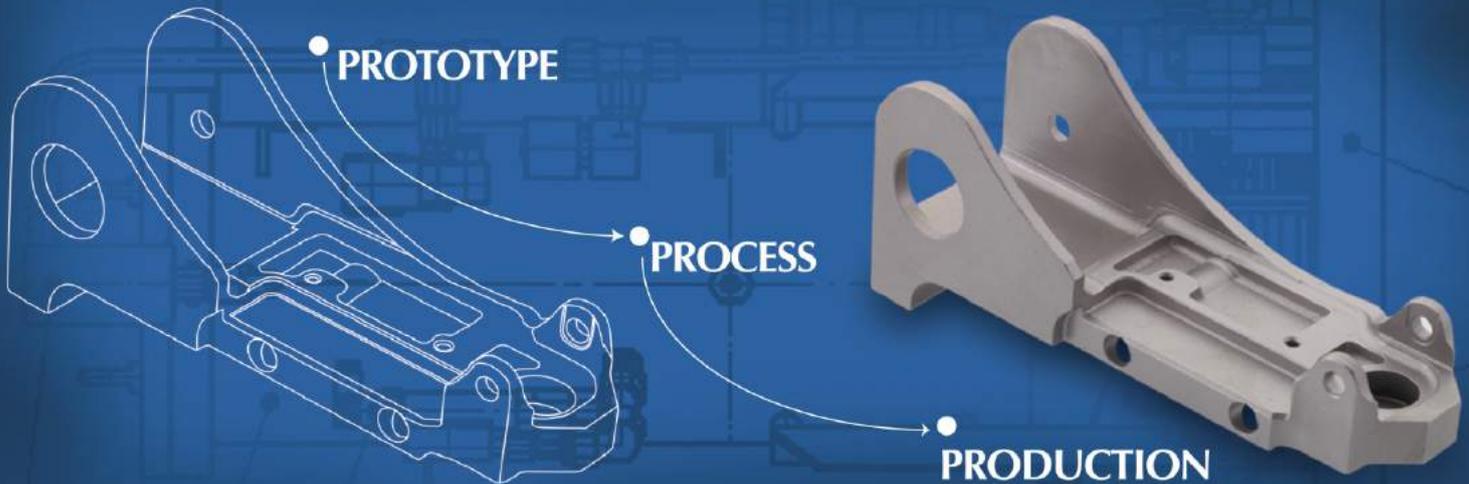


Fig. 3 X-ray CT of the sintered sample, approx. 15 x 15 mm (Courtesy Ricoh)

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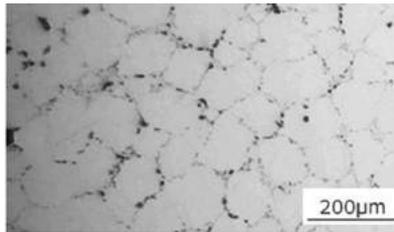


Fig. 4 Grain sizes were approximately 50 µm, equivalent to a typical cast part (Courtesy Ricoh)

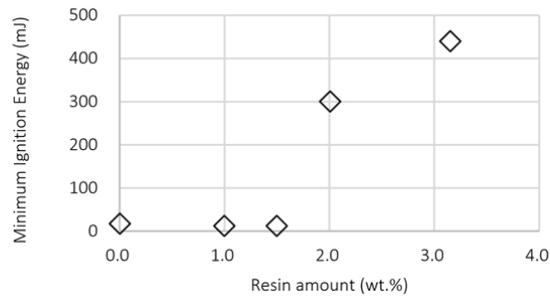


Fig. 5 Resin coating amount / minimum ignition temperature (Courtesy Ricoh)

The relationship between the amount of powder coating resin and the minimum ignition energy is highlighted in Fig. 5, showing that when the resin amount exceeds 2 wt.%, the minimum ignition energy increases, greatly stabilising the coated powder in comparison to

uncoated powder. The researchers state that the resin coating appears to suppress the transfer of explosive energy between particles.

This testing confirmed that it was possible to form 90 mm long internal channels with diameters of 2 mm. The company states that

it is now working on the creation of a prototype with a larger build chamber and even thinner internal channels. The team is also working to expand the range of alloys that this method can be used with.

www.ricoh.com ■

Syqe Medical turns to XJet for high-temperature ceramic parts

XJet Ltd., Rehovot, Israel, reports that Syqe Medical, Tel Aviv, Israel, a pharma-tech company and manufacturer of a revolutionary medical inhaler, is using XJet NanoParticle Jetting™ (NPJ) technology to create parts which are said to be impossible to produce with other manufacturing methods.

Syqe Medical's Selective-Dose inhaler aims to increase the effectiveness of patient treatment by delivering a range of drugs at breakthrough levels of precision. This allows patients to reach the optimum balance between symptom relief and adverse events, and regain their quality of life.

Finding a need to build a high-precision, high-temperature and electrically-insulated test facility for product development, Syqe Medical first looked to PEEK materials and traditional manufacturing methods because of the heat resistance requirements. However, Perry Davidson, Syqe Medical's founder and

CEO, notes that design processes were constrained, requiring many adjustments; consequently, production costs were high, delivery times long – yet still the materials were not durable enough.

"Realising we needed another solution, we turned to XJet," commented Itay Kurgan, Product Manager at Syqe Medical. "We have a wealth of experience with Additive Manufacturing technologies and whilst the polymer materials don't have the heat resistance we needed, XJet ceramic materials are resistant to temperatures even higher than our requirements and of course they are electrically insulated."

"Minor design adjustments are very easy, and results are precise and repeatable, so we can achieve optimum accuracy and delivery times are very fast," he continued. "Where all other options were flawed in at least one aspect, XJet provided the perfect solution."

The XJet Carmel 1400 AM machine, which features the company's patented NPJ technology, produces ceramic parts with super-fine details, smooth surfaces and high accuracy which are preserved with the use of soluble support material, explains Syqe Medical.



Syqe Medical states that XJet ceramic materials deliver the high-temperature resistance and electrical insulation needed for the company's new test facility (Courtesy XJet Ltd)

Dror Danai, XJet CBO, stated, "Syqe Medical is making life-changing advancements in the field of patient care so, we're delighted to see them reaping the rewards of XJet's unique capabilities. Ceramics have some very valuable material properties, but it can be difficult to exploit them due to difficulties in the manufacturing process. XJet delivers all the benefits of ceramic materials, with accuracy and precision, but without the difficulties of traditional manufacturing."

www.xjet3d.com

www.syqemedical.com ■



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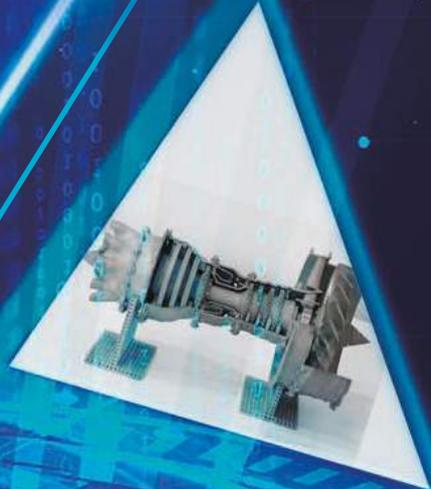
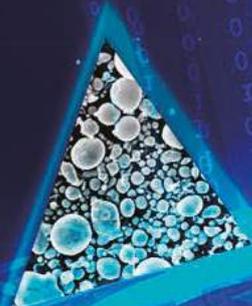
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BASF's Forward AM launches Ultrafuse 17-4 PH filament for metal AM applications

Forward AM, an Additive Manufacturing solutions brand of BASF 3D Printing Solutions GmbH, headquartered in Heidelberg, Germany, has launched Ultrafuse® 17-4 PH for the Material Extrusion (MEX)-based Additive Manufacturing process Fused Filament Fabrication (FFF). The

new filament, combining stainless steel powder with a polymer binder, complements the company's existing Ultrafuse 316L filament.

Offering high mechanical strength and hardness, the new AM material is said to be ideally suited for a wide range of applications, such as tooling,



The new metal filament Ultrafuse 17-4 PH (Courtesy Forward AM)

jigs and fixtures, and functional prototypes, states Forward AM. Good corrosion resistance and the ability to be fully heat treated to high levels of strength and hardness make Ultrafuse 17-4 PH a suitable choice for a range of industries including petrochemicals, aerospace, automotive, and medical, it added.

Ultrafuse metal filaments are specifically developed to work on all common open source FFF machines, from beginner to industrial level, which the company notes makes it one of the easiest and most cost-effective technologies in metal Additive Manufacturing. In 2019, Forward AM launched the company's first metal filament with Ultrafuse 316L.

"Ultrafuse 17-4 PH is an outstanding result of our strong R&D commitment," commented Firat Hizal, Head of Metal Systems Group, BASF 3D Printing Solutions. "We filamented more than ten different metals from titanium to tool-grade steels, and several alternative materials to print support structures within this year. Going forward we will continue to introduce the new filaments that the market and our customers demand."

Hizal added, "We have already established a distribution network that collaborates closely with our debinding and sintering service partners in different regions and can thus deliver an integrated end-to-end solution. We are proud to extend our portfolio with Ultrafuse 17-4 PH."

www.forward-am.com ■

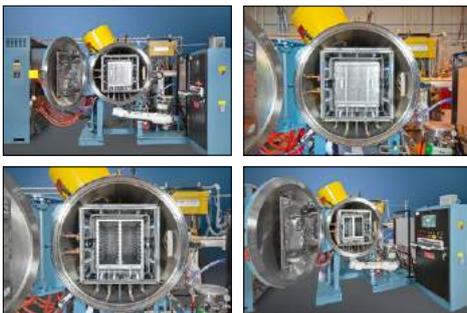


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New dates announced for Ceramitec as 2021 event postponed

The next edition of Ceramitec will now be held from June 21–24, 2022. Typically held once every three years, the trade show last took place in April 2018, but the decision has been taken by the organisers, Messe München, in close cooperation with the Exhibitors' Advisory Board, to postpone the 2021 event due to current trade fair policy. Ceramitec is one of the leading international trade shows for ceramics, and covers the full spectrum of the industry from classic ceramics to raw materials, heavy clay and industrial ceramics, through to technical ceramics and Powder Metallurgy. In total, 633 exhibitors from thirty-eight countries and more than 15,000 participants from ninety-three countries attended Ceramitec 2018.

"From today's perspective, Ceramitec could take place thanks to Messe München's sophisticated

protection and hygiene concept," stated Gerhard Gerritzen, a member of Messe München's Management Board and responsible for ceramitec. "However, due to trade fair policy reasons, the Exhibitors' Advisory Board has asked for a postponement to the year 2022. We comply with this proposal."

"We are all convinced that postponing the event by one year with the opportunity to have Ceramitec running in parallel to Analytica and Automatica is the right way to realise a successful fair on-site with the usual high share of international participants. We will continue to develop and digitally complement our platform to add fresh momentum to the ceramics industry – both at our home base in Munich and worldwide," Gerritzen concluded.

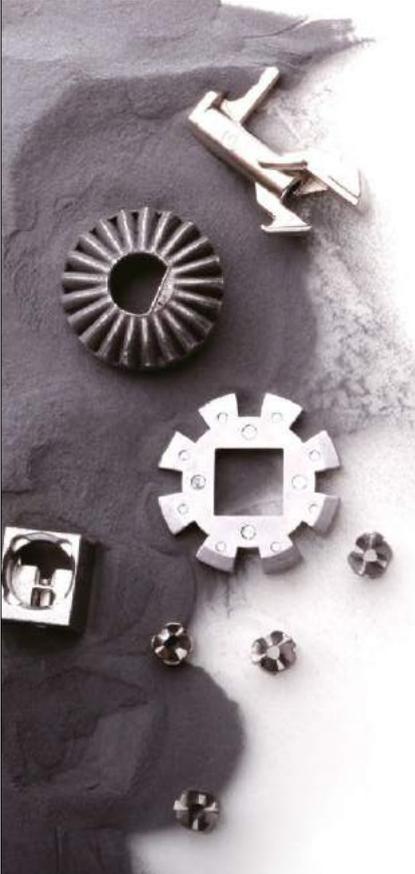
www.ceramitec.com ■

Call for Papers for Euro PM2021

The European Powder Metallurgy Association (EPMA) has issued a Call for Papers for its Euro PM2021 Congress & Exhibition, which will take place in Lisbon, Portugal, on October 17–20, 2021. Authors are invited to submit abstracts of papers for presentation which will be allocated to oral and poster sessions by the Technical Programme Committee (TPC).

Oral sessions will each contain four presentations, with twenty minutes scheduled for each paper, including discussion time. Poster presentations will be in allocated topic zones and will be on display for the duration of the event. Abstracts should be submitted using the EPMA's online submission form before the deadline of January 20, 2021. Further information is available via the organiser's website.

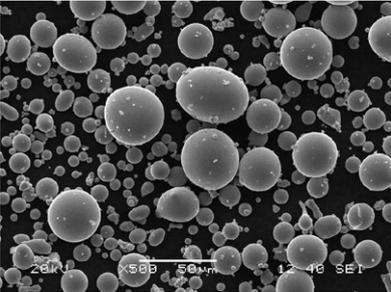
www.europm2021.com ■





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LightForce Orthodontics raises \$14 million in Series B funding round

LightForce Orthodontics, Cambridge, Massachusetts, USA, a digital platform specialising in orthodontics has raised \$14 million in a Series B funding round led by Tyche Partners with follow-on investment from Matrix Partners and AM Ventures.

Founded in 2015 by Dr Alfred Griffin, DMD, PhD, MSc along with Dr Lou Shuman, DMD, LightForce enables orthodontists to utilise its Additive Manufacturing technology to create custom braces for each individual patient, significantly reducing the number of adjustment visits needed. The company explains that it will use the new funds to further develop its technology and product offerings, as well as to scale operations to meet the recent surge in demand for more efficient dental technologies.

Weiji Yun, Managing Partner at Tyche Partners, stated, "We're always looking for visionary entrepreneurs utilising the latest cutting-edge technologies to transform and revolutionise industries. Alfred and Lou's inspirational vision offered us an opportunity to expand our 3D printing investment portfolio and the company's rapid growth is proof that the industry is primed for a solution that improves the orthodontic experience for patients and doctors

alike. We are pleased to partner with such an impressive team of doctors and engineers and contribute to LightForce's success."

Currently, a vast majority of orthodontic cases are treated with the same 'one-size-fits-all' braces that have been used for decades, states the company. LightForce's platform enables mass-customisation to better treat each individual patient through a highly-integrated platform that helps orthodontists determine the best treatment plans and create each patient's unique bracket system.

Orthodontists who treat patients with LightForce technology begin the process by sending LightForce technicians a scan of the patient's teeth and their treatment plan. The LightForce team then creates the fully-customised brackets and trays and sends them directly to the practice for the orthodontist to efficiently bond to the patient's teeth via trays.

LightForce technology uses ceramic material which is said to be virtually identical to injection moulded brackets, but is specially formulated for Additive Manufacturing. Dr Alfred Griffin, LightForce CEO and co-founder, stated, "Braces haven't changed in

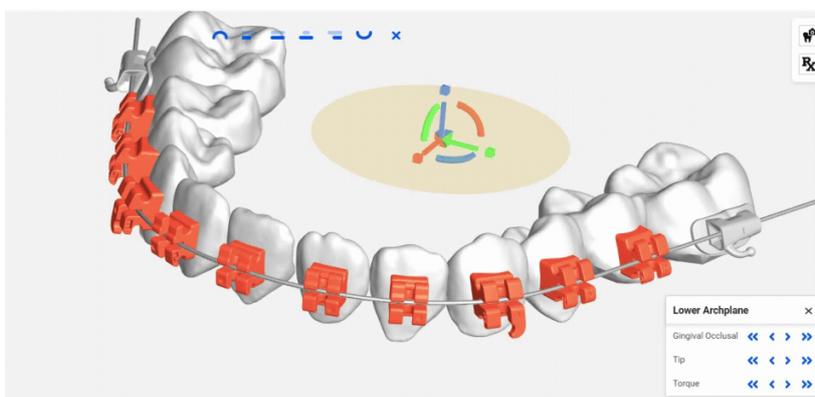
fifty years yet are by far the most common treatment tool; aligners are esthetic and patient-specific, but because of patient compliance and biomechanical limitations, they only serve a small fraction of our patients today."

"This opportunity to help patients and orthodontists was why we applied modern 3D software and 'mass-customisation' to what we know today as 'braces'," he continued. "We've seen LightForce provide shorter treatment times, fewer appointments, and an overall more efficient experience for patients and doctors. In the last year our business has doubled every quarter, and that tells me that LightForce has pinpointed a true need within the orthodontic space. We look forward to growing with our investors, partners and the orthodontic community to provide the best experience and outcomes for our patients."

LightForce offers a variety of products which include:

- LightPlan (Treatment Software by LightForce) – With complete control of every aspect of the treatment plan and a simple cloud-based interface for adjustments and approvals
- Cloud Brackets (Braces by LightForce) – LightForce's Cloud brackets are white, patient-specific AM ceramic polycrystalline alumina brackets
- LightTray (Indirect Bonding Trays by LightForce) – The LightTray is a patient-specific indirect bonding (IDB) tray additively manufactured from a proprietary material. The tray design is the result of seven 3D algorithms unique to LightForce that are all intended to optimise the clinical user experience and bonding accuracy
- TurboTrays (Bite Turbos by LightForce) – LightForce TurboTrays are additively manufactured to aid in the patient's bite correction.

www.lightforceortho.com ■



LightForce Orthodontics will use the new funds to further develop its technology and product offerings (Courtesy LightForce Orthodontics)



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Ruger completes acquisition of Marlin Firearms

Sturm, Ruger & Co., Inc., Southport, Connecticut, USA, a leading manufacturer of firearms for the commercial sporting market, has completed the acquisition of substantially all of Marlin Firearms' assets, as of November 23, 2020.

Established seventy years ago, Ruger offers consumers almost 800 variations of more than forty product lines. Ruger also operates a Metal Injection Moulding facility, Ruger Precision Metals (formerly Megamet Solid Metals Inc.) in Earth City, Missouri, USA, that makes components for its own firearms production as well as serving external customers.

The company states that the agreement to purchase the assets of Marlin Firearms stemmed from the bankruptcy of Remington Outdoor Company, Inc. and was approved by the United States Bankruptcy Court

for the Northern District of Alabama on September 30, 2020. The purchase price of approximately \$28.3 million was reportedly paid with available cash on hand.

Christopher J Killoy, Ruger CEO, commented, "Since we announced the agreement to purchase Marlin in September, we have heard from countless members of the firearms community – consumers, retailers, distributors, writers, and collectors – who are delighted that legendary Marlin rifles are now part of the Ruger product family."

"We are excited to start moving these assets to our Ruger facilities and setting up the manufacturing cells that will produce Marlin rifles for years to come. We look forward to re-introducing Marlin rifles in the latter half of 2021," he concluded.

www.ruger.com ■

MIM2021 virtual conference and PIM tutorial

The virtual edition of the MIM2021: International Conference on Injection Molding of Metals, Ceramics and Carbides, is set to take place on February 22–25, 2021. The conference will include presentations on the latest advancement Metal Injection Moulding and related technologies, including advances in applications, materials and processing.

Delegates will benefit from e-handouts of the presentations as well as a virtual exhibit featuring the latest process and product innovations and access to several industry publications.

An optional PIM Tutorial will be instructed by Matt Bulger, the former president of MIMA (Metal Injection Molding Association).

www.MIM2021.org ■

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Formnext Connect celebrates success as a digital hub for AM

The organisers of Formnext, Mesago Messe Frankfurt GmbH, report that on the first Formnext Connect successfully fulfilled its role as an international digital hub for the AM world, highlighting, even in challenging times, the continuing importance of one of the world's leading exhibitions for the Additive Manufacturing industry.

The digital event, which ran from November 10–12, attracted 203 exhibitors, with about 2,200 representatives, and showcased 1,412 products. Approximately 8,500 active participants from more than a hundred countries used the event's AI-powered matchmaking function, which generated more than 450,000 product and networking recommendations.

In addition, 23,311 new connections were made between attendees and 4,733 business meetings held in the form of video calls. In a programme of 221 lectures and presentations, a range of global experts discussed current and future trends, developments and applications for AM.

"The newly-developed digital format of Formnext Connect has enabled us to meet the demand from the AM

community and target industries for dialogue, business, and innovation," commented Sascha F Wenzler, vice president Formnext at Mesago Messe Frankfurt GmbH. "Formnext has thus demonstrated that, even in a purely digital format, it is indispensable as a globally-important catalyst for the technological and economic development of this future-oriented industry."

Accompanying Formnext Connect was the varied programme from the 'Additive Manufacturing Capital Studio', featuring a number of high-profile guests. This was broadcast on the main stage in consideration of different timezones and featured discussion panels among technology experts from the various exhibitors as well as interviews with representatives from various user industries, including automotive, aerospace, construction, mechanical engineering, medicine, and tool and mould-making.

Wenzler believes that the success of the digital format will also play a role in future trade fair formats. "Born out of necessity due to the worldwide corona [COVID-19] restrictions, Formnext Connect has proven itself



Formnext Connect's programme of stage events and sessions were watched by 45,000 spectators (Courtesy Mesago Messe Frankfurt GmbH)

as a digital platform and will continue to form an important part of future exhibitions," he stated.

Despite this, Wenzler states that he is of the firm belief that the digital format can never make up for the direct contact and personal interaction of a physical event: "That is why we look forward to future editions of Formnext, which we hope will once again be held in person, so that we may bring the vibrant Formnext atmosphere, which we are all familiar from previous years, back to the Frankfurt show floor."

The next edition of Formnext is scheduled to take place in Frankfurt, Germany, from November 16–19, 2021.

www.formnext.com

PMCC&AC EXPO 2020 reports success and announces dates for 2021 show

The Shenzhen International Powder Metallurgy, Cemented Carbide & Advanced Ceramics Exhibition (PMCC&AC EXPO) 2020 was held from September 13–15, at The Shenzhen Convention and Exhibition Center in Shenzhen, China.

According to the event organisers, which include Wise Exhibition (Guangdong) Co., Ltd., Guangzhou Machine Tool & Tool Industry, and Dongguan Numerical Control Cutting Association, the PMCC&AC EXPO 2020 covered an area of 15,000 m² and attracted 19,310 visitors from a number of different cities. Thirty-two purchasing

groups also joined the event, including Foxconn and Huawei.

Due to the coronavirus (COVID-19) pandemic and the resulting restrictions placed on travel and the changes to working patterns, more enterprises were said to be focusing on the domestic market. Over 200 companies participated in the exhibition, where they exhibited raw and auxiliary materials, products and equipment relevant to Metal Injection Moulding, Powder Metallurgy and Additive Manufacturing.

Running alongside the exhibition was the 2020 Shenzhen

International Powder Metallurgy Technology Development Forum. During the forum, presentations were given by experts including Dr Q, Chief Lecturer, You need Technology Office; Dr Yu Peng, Southern University of Science and Technology; and Prof Li Xiaofeng, North University of China. The Second International Symposium on Amorphous Alloy Powder Technology and Application and The 10th China Small Motor & Magnetic Materials Industry Development Summit were also held alongside PMCC&AC Expo 2020.

The 2021 Shenzhen International Powder Metallurgy, Cemented Carbide & Advanced Ceramics exhibition will be held from July 1–3, 2021.

www.pmccepo.com ■

Wall Colmonoy adds Desktop Metal Shop System

Wall Colmonoy Limited (UK), Pontardawe, Wales, UK, the European headquarters of the global powder and components manufacturer Wall Colmonoy, has purchased a Desktop Metal Shop System from UK-based Additive Manufacturing equipment reseller Tri-Tech 3D.

Desktop Metal's Shop System was launched during Formnext 2019. The high-speed, single-pass system was designed to introduce high-quality metal Binder Jetting (BJT) to the market of machine shops and metal fabrication job shops, a global industry estimated to be worth nearly \$180 billion.

The Shop System can be used to additively manufacture end-use metal parts for a variety of industries, including manufacturing, tooling, automotive, consumer electronics,

and marine, with the quality, surface finish and tolerances needed to co-exist with machining.

Wall Colmonoy is reported to be the first company in the UK to purchase a Desktop Metal Shop System. Having been established as a materials engineering business for over eighty years, the company serves the aerospace, automotive, glass, oil & gas, mining, energy, and other industrial sectors. Its Pontardawe facility recently celebrated its fifty-year anniversary.

The company has seen a surge in requirements from existing and new customers for highly-complex parts and tooling in recent years. With the Shop System, it will use Binder Jetting alongside sophisticated software to maximise its Additive Manufacturing efficiency and effectiveness.

Chris Weirman, Director of Technology at Wall Colmonoy Limited (UK), stated, "We identified the Desktop Metal Shop System as the ideal choice for our first step in the metal AM journey due to its speed, size and flexibility, plus the relationship between Desktop Metal and its UK reseller Tri-Tech 3D. This builds upon our knowledge of polymer 3D printing for complex investment-cast forms."

The Shop System is already said to be allowing Wall Colmonoy to partner with several Additive Manufacturing customers. The company now supports the design, prototype, and product qualification of AM parts for customer-specific requirements, and can also develop solutions to overcome existing technical challenges.

www.desktopmetal.com
www.wallcolmonoy.com
www.tritech3d.co.uk ■

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Comparing cost and environmental impact assessment of Binder Jetting and MIM to produce microreactor plates

Manufacturing process design (MPD) is used to model environmental impacts and will become increasingly important in the assessment of the technical advantages and disadvantages of different manufacturing processes for specific products. MPD investigates the physics and the chemistry of the capital equipment, shaping tools and work holding tools for the unit manufacturing processes (UMPs) for a product, in order to generate supporting process flows and related costs in a bottom-up manner. Life cycle analysis (LCA), meanwhile, functions by (1) defining the goal and scope of the study, conducting both (2) an inventory analysis and (3) an environmental impact assessment and (4) interpreting results.

Research undertaken at the School of Mechanical, Industrial and Manufacturing Engineering, Oregon State University, and HP Inc., both located in Corvallis, Oregon, USA, provides a comprehensive cost and environmental assessment of producing a specific product, namely microreactor plates, using both Binder Jetting (BJT) Additive Manufacturing and Metal Injection Moulding (MIM). Results of the research have been published in a paper by Kamyar Raoufi, *et al.* in *Procedia Manufacturing*, Vol. 48, 2020, 311-319. The paper was originally scheduled to be presented at the 48th SME North American Manufacturing Research Conference (NAMRC 48), which was cancelled due to the coronavirus (COVID-19).

The microscale chemical reactor plates are made from 316L stainless steel and are used to convert syngas into dimethyl ether (DME) at operating temperatures of 250–280°C and pressure of 7–20 bar. Fig. 1 shows an exploded assembly view of the DME plate reactor with three plates. In this study, the top plate was not included, as its design allowed it

to be economically produced using conventional subtractive methods such as laser cutting.

Metal BJT and MIM were both studied for production of the middle and bottom microreactor plates used in dimethyl ether production and the authors compared the two manufacturing processes for annual production volumes ranging from 1,000 to 100,000 parts. They stated that, whilst the technical advantages and disadvantages of MIM and BJT have been explored in prior research, little has been reported on the relative sustainability of their performance.

Binder Jetting does not directly fuse the metal powder layers, as in Powder Bed Fusion (PBF) AM, but rather uses a binding agent to bond the powders together layer by layer, creating a green part. The BJT process does not, therefore, require a heat source to produce the green part, reducing cycle time and improving cost-effectiveness relative to PBF in high production volumes for many applications.

The basic process flow for producing microreactor plates using BJT involves four major steps: building, depowdering, debinding and, finally, sintering. The AM process starts with spreading a layer of 316L stainless steel powder, followed by depositing the binder, and finally by curing the powder/binder layer using a heat source (e.g. a lamp). This cycle repeats until all layers of the green part are built. The green part then undergoes debinding and sintering.

MIM involves injection moulding of the 316L stainless feedstock to produce a green part, followed by primary debinding to produce the brown parts, removal of the secondary binders by thermal debinding, then sintering to densify the material and provide the required properties.

The authors reported that the required materials, consumables and utilities for each UMP under both

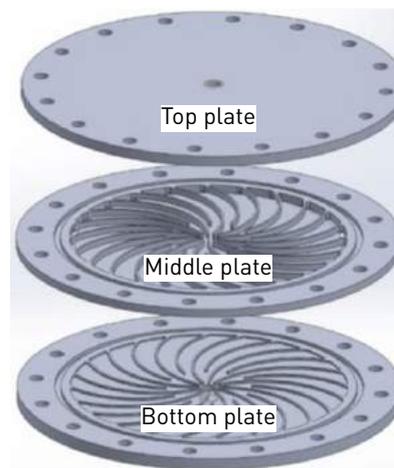


Fig. 1 Exploded assembly view of DME microreactor plates (From paper: 'Cost and environmental impact assessment of stainless steel microreactor plates using binder jetting and metal injection moulding processes', by K. Raoufi, *et al.*, *Procedia Manufacturing*, Vol. 48, 2020, 311-319)

production scenarios were obtained from the MPD analysis. The life cycle inventory (LCI) data for the processes in the system boundary were captured from the literature and by consulting with design and manufacturing practitioners, as well as using the ecoinvent 3 database.

Detailed materials and energy inputs for the BJT and MIM processes flows are reported. SimaPro 9, an industry-standard LCA software, was used to capture data and conduct the impact assessments. Impact assessments used the cumulative energy demand (CED), IPCC 2013 V1.03, and ReCiPe 2016 methods. CED was said to capture indirect and direct energy use over the life cycle. The IPCC 2013 method applied assumes a 100-year time horizon to estimate global warming potential.

The production cost models for the cost of goods sold (COGS) showed a reduction of COGS with increasing annual production for the middle and bottom reactor plates using the MIM and BJT processes, as can be seen in Fig. 2. MIM results in lower COGS than BJT for all production volumes. At 1,000 reactors per year, the unit cost for MIM (\$294) is 17% lower

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than for BJT (\$356). As production volume increases to 10,000 reactors per year, COGS for both processes decrease with the same relative cost savings, while at 100,000 reactors per year, COGS for MIM is 22% less than that for BJT.

Using the production cost curves by cost elements and process steps, it was found that the main cost driver was capital tooling cost. Specifically, MIM was found to have lower capital tooling cost, coupled with a shorter cycle time for making the green part. Equipment utilisation in the injection moulding step exceeds the capacity of a single tool at a higher production volume (100,000) than the equipment in Binder Jetting (20,000). The other key cost driver in the BJT process was the labour cost associated with the depowdering step.

The authors established that the labour cost in the BJT process is double that for the MIM process at an annual production volume of 1,000 reactors. Labour costs were found to decrease as the annual production volume increases, but still remained higher in BJT compared with MIM. This cost differential indicates an opportunity for improving the economic performance of the Binder Jetting process by automating the current manual depowdering step.

Life cycle assessment results indicate that the MIM process has higher environmental impacts than

BJT for an annual production volume of 1,000 reactor plates. Impacts are mainly due to consumables, primarily the mould in the injection moulding step and the solvent in the debinding step. As production volume increases, however, the environmental impacts per part reduce significantly for the MIM process due to amortising the associated impacts of the mould and solvent across more products. However, this effect of amortisation is not as apparent for the BJT process since the main environmental drivers are raw material and the utilities.

The authors concluded that, in order to analyse and compare manu-

facturing alternatives, the products explored should be producible by all selected processes. For example, to investigate the potential advantages of a broader set of metal Additive Manufacturing processes over MIM, which is limited by moulding, more complex geometries (product shapes and sizes) should be investigated. This would provide richer information for design and manufacturing decision makers about process capabilities, production costs and product environmental impacts for various product complexities.

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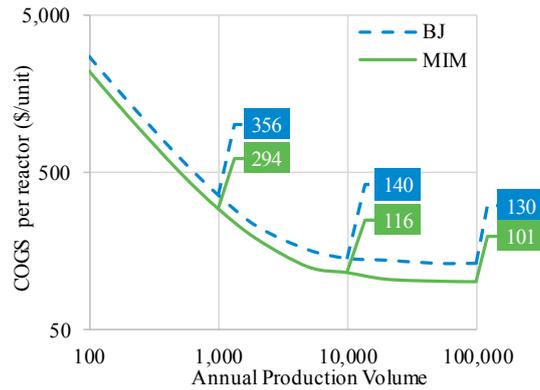


Fig. 2 Effect of annual production volume on cost of goods sold (COGS) for the production of DME microreactor plates using the MIM and BJT processes (From paper: 'Cost and environmental impact assessment of stainless steel microreactor plates using binder jetting and metal injection moulding processes', by K. Raoufi, et al., Procedia Manufacturing, Vol. 48, 2020, 311-319)

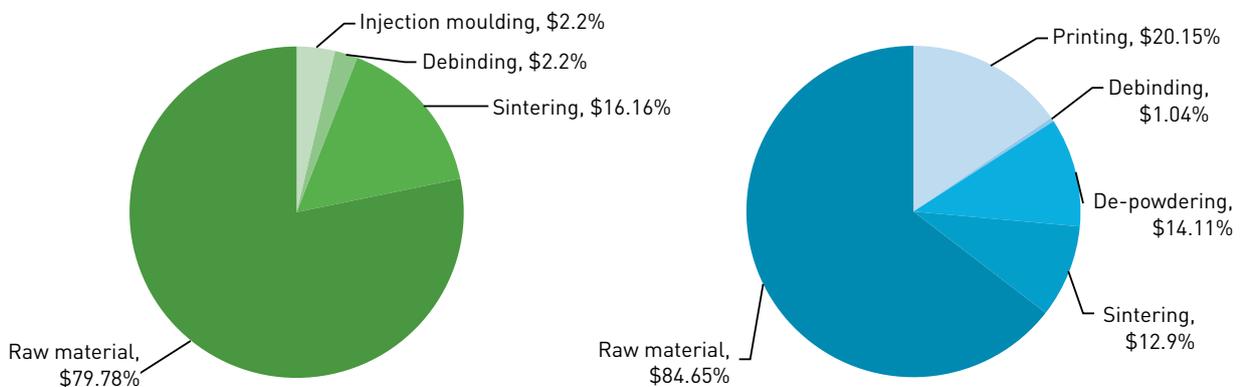


Fig. 3 Cost breakout by process step using the MIM (left) and BJT (right) processes for an annual production volume of 100,000 reactors (From paper: 'Cost and environmental impact assessment of stainless steel microreactor plates using binder jetting and metal injection moulding processes', by K. Raoufi, et al., Procedia Manufacturing, Vol. 48, 2020, 311-319)



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Simulation of low-pressure Powder Injection Moulding of metallic feedstock

Injection moulding is one of the most important stages in the process of shaping a PIM component while avoiding defects such as sinks, voids, dead zones, warpage, cracks and faulty weld lines. Conventional 'high-pressure' PIM already successfully uses numerical simulation software packages to optimise the injection moulding of defect-free, complex components from metallic feedstock. However, numerical models predicting the flow behaviour of metallic feedstock using Low-Pressure Powder Injection Moulding (LPIM) have received very little attention to date.

A research project carried out with the support of MITACS Globalink Graduate Fellowship and the AeroCREATE Program in Competitive Manufacturing for the Aerospace Industry undertaken by the Ecole de technologie superieure, Montreal, Canada, sought to develop the first simulation of LPIM for metallic feedstock, and a research paper outlining the results of the research was published by Mohamed Aziz Ben Trad and colleagues in the journal *Advanced Powder Technology* Vol. 31, 3, March 2020, pp 1349-1358.

The authors stated that main advantages of LPIM are related to the relatively low production costs combined with the flexibility to design

highly complex shaped components. They further stated that, over the past thirty years, conventional high viscosity feedstocks (e.g., 10^3 Pa·s), typically injected at pressures ranging from 50-200 MPa, have been modified to develop lower-viscosity feedstocks suitable for the LPIM process and injected at a pressure generally lower than 700 kPa. The viscosity values of these new generation feedstocks are typically in the 1-20 Pa·s range, but generally lower than 10 Pa·s, to accommodate an LPIM press using air pressure.

Numerical simulations are already used to predict the flow behaviour for ceramic-based feedstocks during the injection stage of LPIM, but, as stated above, this is not the case for the LPIM of metallic feedstock, where injection parameters and feedstock properties are currently still defined using empirical trial and error techniques.

The aim of this study was, therefore, to verify the ability of the Moldflow simulation software tool to represent the physical phenomena associated with the injection stage of LPIM metallic feedstock. The authors used Moldflow Synergy 2019 (Autodesk Inc) to perform numerical simulations of injection moulding to produce green parts 11.75 mm diameter x 100 mm long in a cylindrical cavity.

The Moldflow software is said to take into account only one particle characteristic, which is the average size of the particles (D50). Input parameters were, therefore, arranged in terms of geometry, material properties and operation parameters, while the output parameters were

Mold temperature (°C)	35
Feedstock temperatures (°C)	80, 90, and 100
Injection flow rate (cm ³ /s)	1.15
Gate position	Bottom centre

Table 1 Boundary conditions and process parameters used for the simulations (From the paper 'Numerical simulation and experimental investigation of mold filling and segregation in low-pressure powder injection molding of metallic feedstock', by Mohamed Aziz Ben Trad, et al., *Advanced Powder Technology*, Vol. 31. No. 3, March 2020, pp 1349-1358)

described as the injection length, the melt front velocity, the filling time, the shear deformation rate profile, the pressure at the gate and the powder volume concentration. The boundary conditions and process parameters used for the simulations are summarised in Table 1, assuming a no-slip condition on the solid walls.

The authors stated that, since the feedstock's properties depended on its formulation, it was necessary to prepare and characterise a powder/binder mixture to increase the quality of the input data for the model and improve the accuracy of the numerical simulation. They prepared feedstock using a gas atomised 17-4PH stainless steel having nominal particle size of 12 µm mixed with a wax-based molten binder (90°C) formulated from four polymeric constituents in the following proportions: 30 vol.% of paraffin wax, 7 vol.% of carnauba

wax, 2 vol.% of stearic acid, and 1 vol.% of ethylene vinyl acetate.

This specific formulation was developed to produce a relatively high viscosity of about 5–7 Pa.s at low shear rates (i.e., near-zero shear rate directly after the mould filling) and a low viscosity < 1 Pa.s for a shear rate > 10 s⁻¹ (i.e., during the mould filling).

The powder and binder were mixed in a planetary mixer under vacuum for 45 min to produce homogeneous feedstock. Powder loading in the feedstock was 60 vol.%. Feedstock properties were characterised using rheological, calorimetry, density, thermal diffusivity and thermogravimetric tests.

Injections were performed using a laboratory injection press in which a new injection concept was developed to minimise segregation of low-viscosity feedstocks and to quantify the full mouldability potential of the LPIM process. Feedstock was heated up to 80, 90, or 100°C,

blended using a planetary mixer at 10 rpm for 15 min under vacuum and then injected to produce the green cylindrical parts. Viscosity profiles obtained at the three different temperatures are shown in Fig. 1. The temperature of the moulds was maintained at 35°C and seven injections were run for each feedstock condition.

VirtualDub software was used to record the mould filling at fifteen frames per second, while the melt front velocity was captured using a superimposed scale in Avimeca and processed using the Regressi software. Between two injections, the feedstock remaining in the injection cylinder was returned into the container to be re-blended. The injection was performed using a controlled constant volumetric flow of 1.15 cm³/s (value at the gate for a Ø15.9 mm), while the injection pressure value was recorded using a load cell located in the injection

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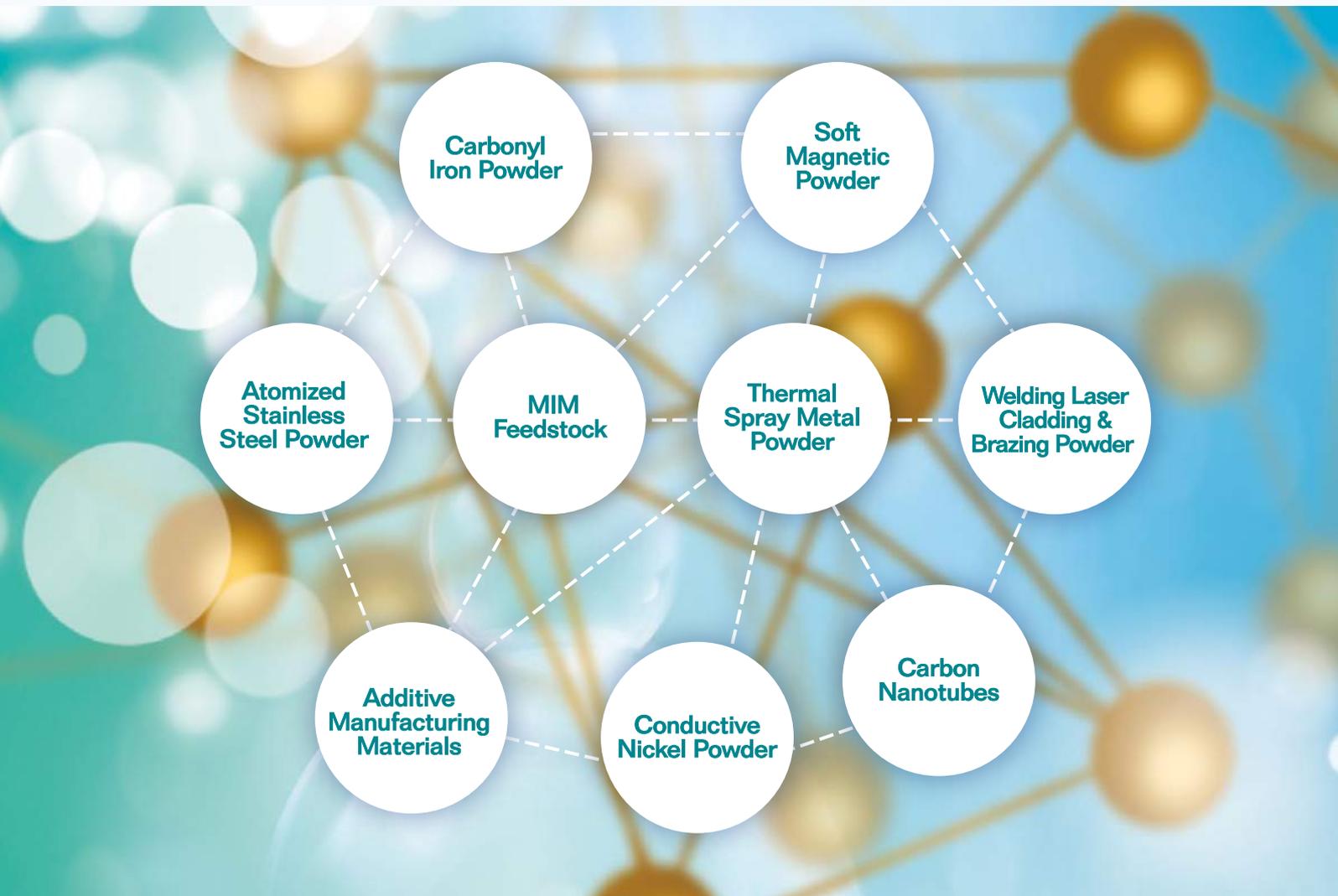
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axis. The filling times, of about 9–10 s, obtained in this study were significantly higher than those generally attained with a conventional LPIM press using air pressure (i.e., filling of the mould cavity in a few tenths of a second). The simulation of segregation after injection was captured by the Moldflow Synergy 2019 package and validated using thermogravimetric analysis.

The authors concluded that the injected length, the melt front velocity and the filling times predicted by the numerical model were in good agreement with the experimental observations, with a relative difference varying from 3.1–4.4%. Also, since the injections were performed and simulated at constant volumetric flow into a constant cross-section mould cavity, the mould filling results confirm that the feedstock temperature has no influence on the injected lengths, but, rather, on the injection pressure.

The absence of segregation during injection was also captured by the software simulation code, where experimental local solid loading measurements confirm the capability of the numerical model to successfully predict the

homogeneous distribution of the powder (i.e., no segregation) within a simple shape mould cavity.

Finally, as the present work, to the authors' best knowledge, represents the first simulation of LPIM of metallic feedstock, the interesting

simulation capabilities observed for the injection behaviour and segregation obtained for simple shape green metallic components should be tested for more complex shape parts in any future work.

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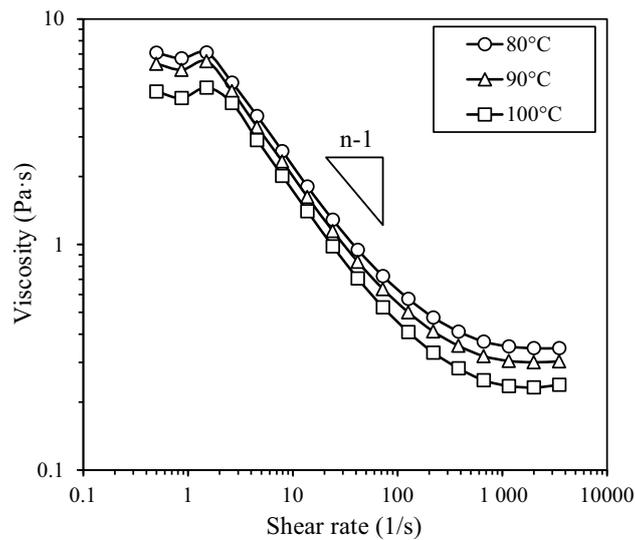
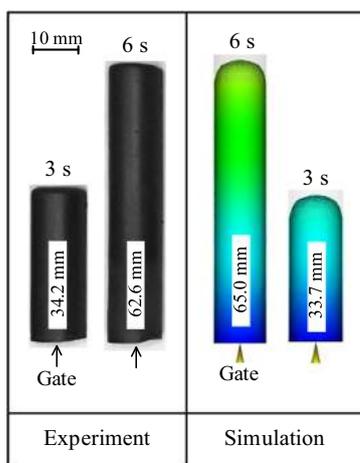


Fig. 1 Viscosity profiles of the 17-4 PH stainless steel feedstock measured at 80, 90 and 100°C [From the paper 'Numerical simulation and experimental investigation of mold filling and segregation in low-pressure powder injection molding of metallic feedstock', by Mohamed Aziz Ben Trad, et al., *Advanced Powder Technology*, Vol. 31. No. 3, March 2020, pp 1349-1358]



(a)

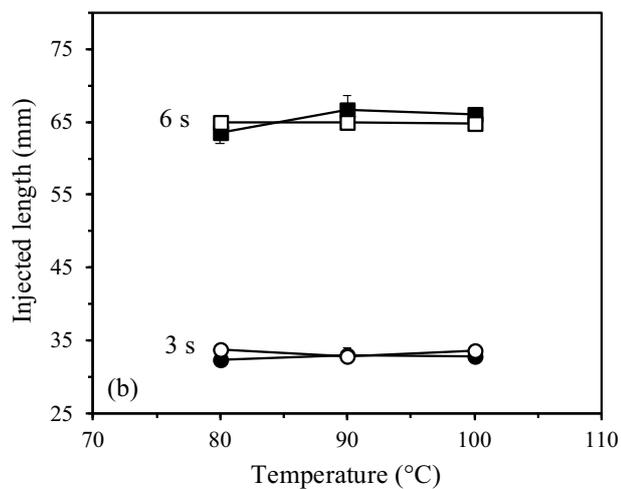


Fig. 2 Experimental and simulated injected lengths: (a) typical results after short shots of 3 and 6 s with feedstock at 80°C, and (b) injected lengths for different injection temperatures, with white symbols for simulation and black for experiment [From the paper 'Numerical simulation and experimental investigation of mold filling and segregation in low-pressure powder injection molding of metallic feedstock', by Mohamed Aziz Ben Trad, et al., *Advanced Powder Technology*, Vol. 31. No. 3, March 2020, pp 1349-1358]

CoCrMo alloy processed by MIM gives good properties for biomedical applications

Cobalt-based alloys, initially containing nickel, which was replaced due to its high allergy risk with elements such as Cr and Mo, have been used widely in the biomedical and dental sectors for many decades. The CoCrMo alloys (ASTM F75, F799) have high strength, including high cycle fatigue, ductility, high corrosion and wear resistance, in addition to meeting the requirements for biocompatibility in terms of cytotoxicity, carcinogenicity, mutagenicity, pyrogenicity and allergenicity.

There is already a significant amount of data available on the properties of cast and wrought CoCrMo alloys used for surgical implants, with cast components showing poorer mechanical properties compared with those which have been forged. However, both the casting and forging processes have limitations regarding the production of complex, net-shape and high-tolerance implant components, and Metal Injection Moulding (MIM) has emerged as a potential manufacturing process, which overcomes these shape limitations. Additionally, MIM offers the potential to better control

the microstructure of F75 alloys, allowing a finer grain size in the sintered alloys, leading to further improved properties.

A team of researchers led by Professor Gemma Herranz, Universidad de Castilla-La Mancha, and Professor Cristina García, Universidad de Valladolid, both in Spain, has undertaken extensive research on the feasibility of producing a low-carbon-content CoCrMo alloy using the MIM process. A paper containing the results of their research work to date was published in the *Journal of the Mechanical Behaviour of Biomedical Materials* (Vol. 105, May 2020, 103706).

The researchers first studied the different stages of MIM processing of the CoCrMo alloy, including mixing of the powder with the binder system, rheological studies, the injection process, and debinding and sintering, followed by subsequent characterisation of the as-sintered samples. Characterisation included both static and dynamic mechanical performance evaluation to estimate the components' durability in real applications, as well as a tribological and corrosion study with different

methods and electrolytic solutions that simulate the biological environment.

The authors stated that the starting material used was a water atomised Co₂₈Cr₆Mo powder (F75) containing 0.085 wt.% C with particle size D₉₀ lower than 18 µm and spherical particles, as can be seen in Fig. 1 (a) and (b). The feedstock used in the MIM process was produced by mixing the appropriate amount of F75 alloy powder with a thermoplastic binder containing High Density Polyethylene (HDPE) and Paraffin Wax (PW) in the ratio HDPE50:PW50. Results showed that feedstock containing 65 vol.% powder loading exhibits adequate torque values and the best flow behaviour.

The feedstock was injection moulded at 180°C to produce cuboid and 'dog-bone' green test pieces, which were subsequently debound in a two-step debinding process: first in heptane at 60°C for 5 h followed by a thermal debinding cycle at up to 450°C. The debound brown shapes were then sintered at 1380°C to achieve the desired carbon content of 0.05 wt.% and hardness of 280 HV. Analysis of the sintered MIM parts' microstructure showed polygonal grains of different sizes, together with residual round-shaped pores (around 1%).

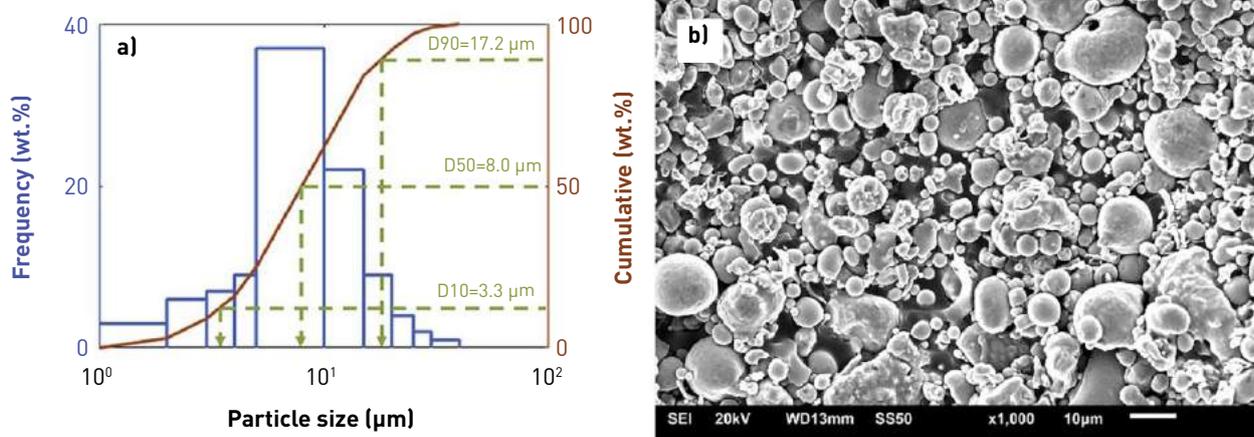
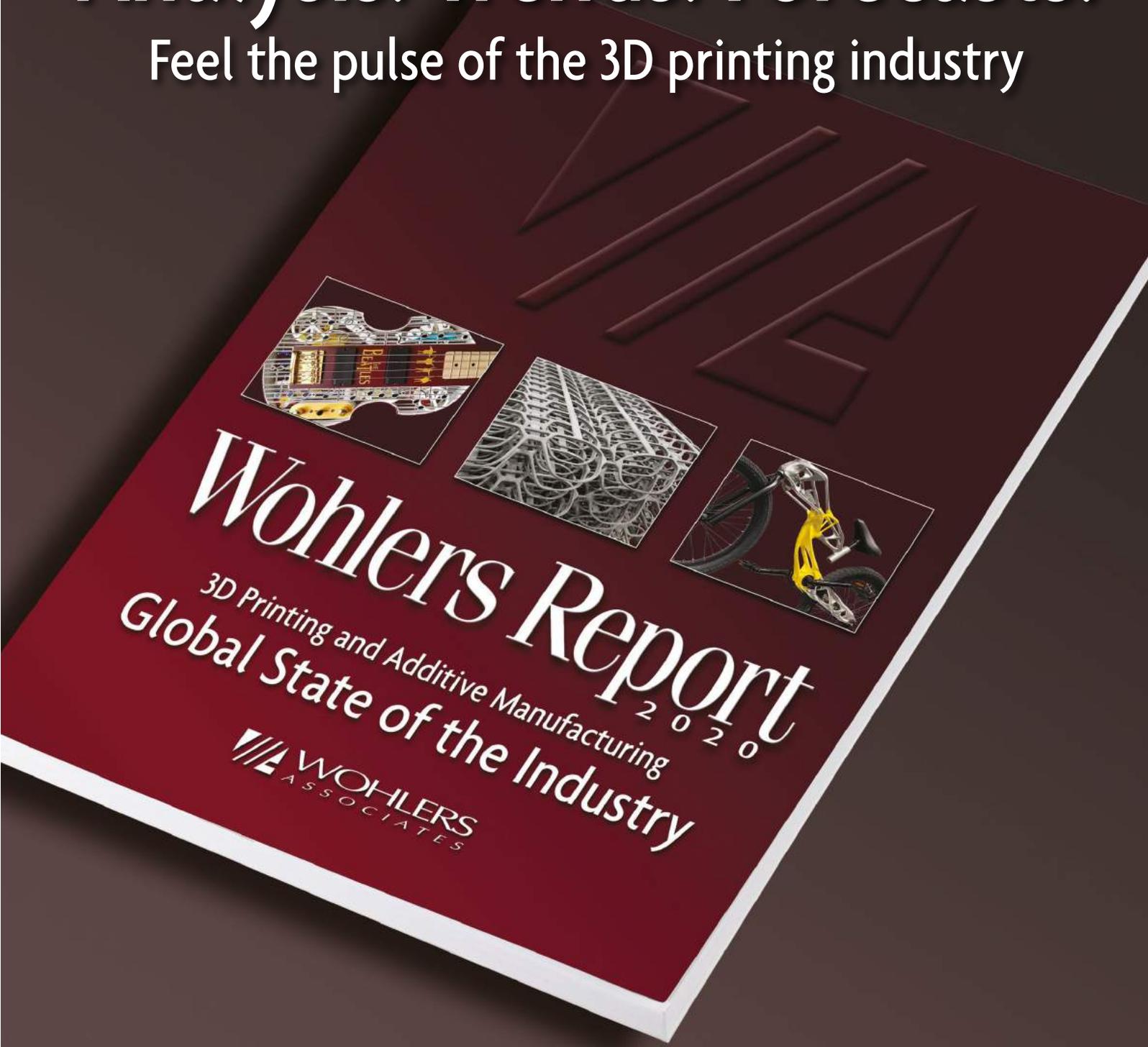


Fig. 1 Granulometry (a) and SEM micrograph (b) of water atomised CoCrMo alloy powder (From paper: 'Mechanical performance, corrosion and tribological evaluation of a CoCrMo alloy processed by MIM for biomedical applications' by G. Herranz et al., *Journal of the Mechanical Behaviour of Biomedical Materials*, Vol. 105, May 2020, 103706.)

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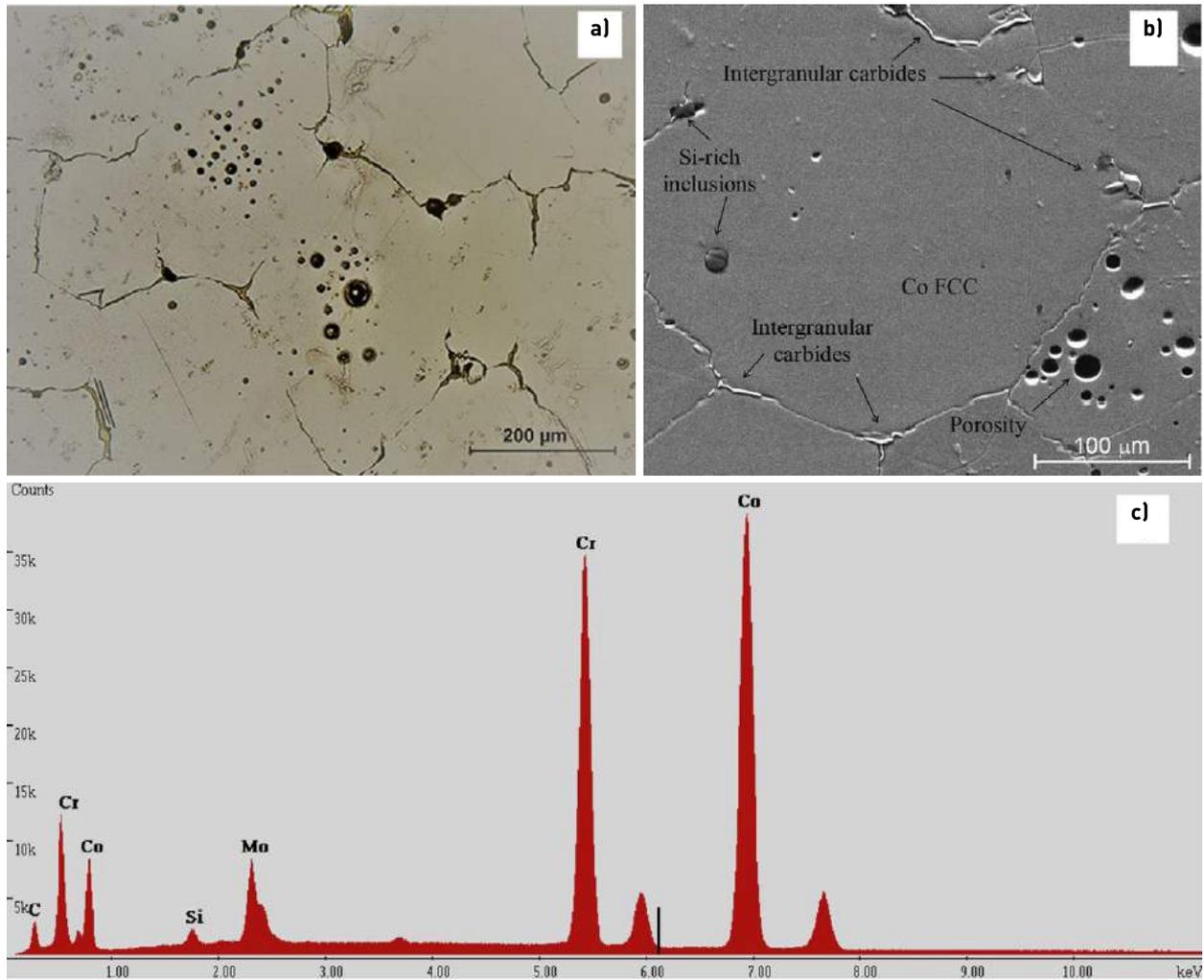


Fig. 2 Microstructural characterisation of the optimised components sintered by LOM-colour etching (a), by SE-SEM (b) and EDX-SEM analysis of the intergranular carbides (c) (From paper: 'Mechanical performance, corrosion and tribological evaluation of a CoCrMo alloy processed by MIM for biomedical applications' by G. Herranz et al., *Journal of the Mechanical Behaviour of Biomedical Materials*, Vol. 105, May 2020, 103706.)

Grain size was found to be in the range 150–200 µm, which pointed to an adequate equilibrium between relative density, microhardness and microstructure.

The low-carbon F75 sintered MIM cobalt alloy produced in this research was found to lead to a small amount of carbides, mainly intergranular carbides, and, although chromium and molybdenum carbides are present in the intergranular region of this material, the homogeneous sintered microstructure achieved still provides high chromium availability to oxide film formation and, therefore, good corrosion resistance (Fig. 2).

The predominant phase in the cobalt alloy after the sintering process is a face-centred cubic (FCC) solid solution, together with a residual hexagonal-centred phase (HCP), as was confirmed by X-ray diffraction characterisation.

Mechanical properties

Key to the application of the MIM CoCrMo alloy in implant applications is its performance after many cycles of use. The authors undertook static testing, such as tensile and bending strength measurements, and determined values for Young modulus, the flexural Young

modulus, the yield strength at 0.2% of permanent deformation, the ultimate tensile strength, the flexural strength and the maximum elongation at fracture. Test results are shown in Table 1.

Regarding the comparison with other forming technologies, the values obtained for MIM were found to be of the same order of magnitude as those typically achieved for casting (ASTM F75), but were below the ASTM F1537 norm for wrought materials. However, the authors stated that further improvements in the mechanical properties of the Ni-free CoCrMo alloys are expected

to be achieved by post-processing treatments such as Hot Isostatic Pressing (HIP) to minimise porosity in the sintered material.

The dynamic properties of the MIM CoCrMo material have also been studied. The results obtained from the four-point bending fatigue tests (10^7 cycles) showed fatigue strength in MIM CoCrMo alloys to be higher than 200 MPa, which was comparable to the cast CoCrMo alloys and acceptable for most applications within the human body.

Corrosion and wear studies

Two types of electrochemical tests were carried out to evaluate the corrosion resistance of the MIM CoCrMo material: the 'Open circuit potential' test to evaluate the thermodynamic corrosion resistance under equilibrium conditions in different environments; and the 'Anodic polarisation test' to evaluate the anodic corrosion behaviour and calculate the corrosion potential

Tensile test	E (MPa)	σ_y 0.2% (MPa)	σ_{max} (MPa)	Elongation (%)
	$16 \cdot 10^4 \pm 3 \cdot 10^4$	420 ± 11	683 ± 11	15 ± 1
Bending test	E_f (MPa)	σ_y 0.2% (MPa)	σ_f (MPa)	Elongation (%)
	$49 \cdot 10^3 \pm 5 \cdot 10^3$	657 ± 25	1433 ± 56	18 ± 2

Table 1 Static mechanical characterisation of sintered CoCrMo parts in terms of Tensile and Bending tests (From paper: 'Mechanical performance, corrosion and tribological evaluation of a CoCrMo alloy processed by MIM for biomedical applications' by G. Herranz et al., Journal of the Mechanical Behaviour of Biomedical Materials, Vol. 105, May 2020, 103706.)

(E_{corr}), the corrosion current density (I_{corr}), the passivation current density (I_{pass}) and the breakdown potential (E_b). The electrochemical tests were performed in three different electrolytic solutions that simulated biological environments: NaCl, Ringer and PBS solutions at $37^\circ\text{C} \pm 1$ in a nitrogen atmosphere.

MIM parts produced from low-carbon CoCrMo alloy were found

to have a higher corrosion potential and lower current density than parts processed by other technologies. Finally, wear parameters confirmed remarkable values for low-carbon cobalt alloys, abrasive and tribo-oxidation being the main wear mechanisms found in pin-on-disk testing.

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Titanium hydride powder addition lowers cost of titanium Metal Injection Moulding

Metal Injection Moulding has played a significant role in the development and production of small, complex-shaped, high-quality, lightweight titanium components having high specific strength, good biocompatibility, oxidation resistance, non-magnetic and non-toxic properties. However, the high cost of spherical titanium powder suitable for processing by MIM has held back the development of many potential new applications in a number of sectors. The reduction in the cost of Ti PIM products has, therefore, long been the challenge and focus of a number of research projects.

Some researchers have prepared Ti MIM samples using less expensive non-spherical HDH or titanium hydride (TiH_2) powder instead of spherical Ti powder, or mixtures of HDH Ti powders and gas atomised spherical Ti powder with naphthalene as the principal binder constituent. Tensile strength comparable to wrought Ti could be achieved. However, there has been limited research on the application of TiH_2 powder for Ti MIM parts using the mainstream POM-based catalytic binder system.

Joint research undertaken at the Guangdong Academy of Sciences in Guangzhou, and the Central South University in Changsha, China, has focused on the use of a POM-based binder with a mixture of lower-cost irregular shape TiH_2 powder (\$30/kg) and gas atomised spherical Ti powder (\$280/kg) with the aim of lowering the overall cost of PIM-produced Ti components. The results of this research were published by Kai Hu and colleagues in *Powder Technology* Vol. 367, May 1, 2020, pp 225-232.

The researchers used an angular, irregular TiH_2 powder having a D50 particle size of 14.9 μm (0.018% C and 0.3% O) whereas the gas atomised spherical pure Ti powder had a D50 particle size of 16.6 μm (0.011% C and

0.1% O). Four different raw material samples were used to prepare the MIM feedstock with the samples T1 and T4 based on only TiH_2 powder and pure spherical Ti powder respectively. The raw materials for samples T2 and T3 were a mixture of TiH_2 powder and spherical titanium powder in the mass ratio of 3:2 and 2:3, respectively.

These samples were mixed with a polyoxymethylene (POM)-based binder system consisting of 88 wt.% POM, 5 wt.% ethylene-vinyl acetate (EVA), 5 wt.% high-density polypropylene (HDPE) and 2wt.% stearic acid (SA). The solids loadings, referring to volume ratios of powder in the feedstock, were T1=50 vol.%, T2=52 vol.%, T3=56 vol.% and T4=60 vol.%, respectively.

Injection moulding was done at a maximum pressure of 95 MPa and with injection temperatures from the barrel to the nozzle being 155°C, 175°C, 180°C, 185°C and 195°C. Catalytic debinding, primarily to remove most of the POM, was done at 120°C for 8 h with nitric acid as the catalytic medium. The remaining POM and SA decomposed and volatilised at 265°C–410°C, while EVA and HDPE decomposed and volatilised at 405°C–510°C.

The thermal debinding, dehydrogenation of TiH_2 and sintering steps were performed in a vacuum furnace at 10–3 Pa. with a holding time of 2 h at 750°C for a thorough promotion of dehydrogenation. The final sintering temperature was set at 1300°C and held for 2 h. The determination of the sintering process parameters for sample T1, T2, and T3 were based on the results of the differential scanning calorimetry (DSC-TG) experiments.

The authors found that, because of the angular and irregular shape of the TiH_2 powder used in sample T1, the binder was not as easily removed as the binder in sample T4, which used only the pure spherical Ti powder.

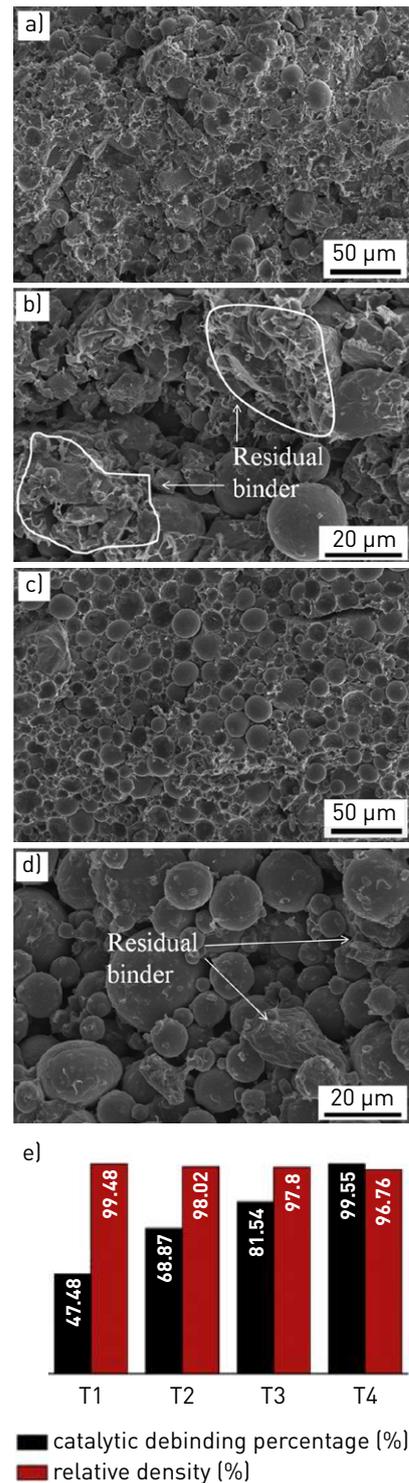


Fig. 1. SEM image of feedstock: (a) T2, (c) T4. SEM image of sample after catalytic debinding: (b) T2, (d) T4. (e) catalytic debinding percentage and relative density of samples (From paper: 'Effect of titanium hydride powder addition on microstructure and properties of titanium powder injection moulding' by Kai Hu, et al., *Powder Technology*, Vol. 367, May 1, 2020, pp 225-232)

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In the use of a mixture of irregular TiH₂ and spherical Ti powders in the feedstocks for samples T2 and T3, there was high friction between the powders, meaning the mixing between the powder and the binder was not uniform, and more POM binder remained adhered to the irregular TiH₂ powder surface.

Further additions of TiH₂ powder to the mix containing pure Ti powder led to increases in the residual POM amount.

Nevertheless, the relative density of the sintered samples T1, T2, T3 and T4 reached 99.48%, 98.02%, 97.8%, and 96.76%, respectively, which suggests that the sintered density of the samples increased with the addition of TiH₂ powder. The authors put this down to the phase change mechanism of TiH₂ powder during the dehydrogenation process. Fig. 1 shows the catalytic debinding percentages, i.e. the ratio of removed POM to total, for samples T1, T2, T3 and T4 were 47.48%, 68.87%, 81.54% and 99.55%, respectively. Fig. 1 also shows the relative densities of the samples and SEM images of the feedstock used.

The authors also concluded that the TiH₂ powder additions to pure spherical Ti powder greatly influenced the microstructure and properties of the samples investigated. The sintered microstructure of the mixed TiH₂ powder and pure Ti powder samples was found to gradually change from

Sample	T1	T2	T3	T4	Ti grade 4 ^a
σ (MPa)	319	507	683	838	550
$\sigma_{0.2}$ (MPa)	163	405	543	729	483
δ (%)	1.1	2.7	5.1	6.3	15
Hardness (HV)	454	389	353	330	221
Abrasion loss (mg)	6.7	8.4	7.9	10.5	14.6
C content (%)	0.22	0.18	0.16	0.12	0.08
O content (%)	0.67	0.48	0.37	0.30	0.4
H content (%)	0.005	0.003	0.002	0.003	0.015

Table 1 Mechanical properties and impurity contents of the sintered samples (From paper: 'Effect of titanium hydride powder addition on microstructure and properties of titanium powder injection moulding' by Kai Hu, et al., Powder Technology, Vol. 367, May 1, 2020, pp 225-232)

basketweave to the β -Ti phase distributed with equiaxed α -Ti phase and in-situ TiC particles were formed with different morphology. This resulted in the TiC-particle reinforced titanium matrix composite having greatly improved strength, hardness and wear resistance, but reduced elongation compared with the T4 sample and the ASTM titanium grade.

The sample T1 was found to have the highest sintered density and hardness values but poorest strength and elongation (Table 1). The mechanical properties of the sintered sample T3 (TiH₂ powder and spherical titanium powder with the mass ratio of 2:3) were slightly

lower to those for the sintered sample T4 (spherical titanium powder).

Increasing the proportion of TiH₂ powder in the T2 samples enhanced the sintered density of the titanium MIM samples, though the strength and elongation values were lower. Wear properties, as measured by abrasion resistance, were significantly improved in samples T2 and T3 compared with sample T4 and the ASTM titanium grade.

The results suggest that the cost of titanium MIM can be significantly reduced by adding TiH₂ powder and the material has potential for applications in several fields, including wearable devices.

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Fig. 2 Black zirconia frame for a gearshift lever [Courtesy Oechsler AG]



Fig. 3 Automotive interior equipment – a selector button made of black zirconia [Courtesy Oechsler AG]

capitalise on these opportunities. Between 2000 and 2009, the Powder Injection Moulding sector as a whole, encompassing both Metal Injection Moulding and Ceramic Injection Moulding, has generally experienced growth, mostly in the range of 8–14% per year [6]. Today, CIM is identified as one of the lead technologies in the field of technical ceramics.

Originally seen as an attractive option for the high-volume production of primarily smaller components [7], the technologies underpinning this forming method have evolved to such an extent that medium- and low-volume runs can be managed effectively and be commercially feasible [8]. Today, CIM technology can deliver components with feature sizes greater than 10 μm , aspect ratios greater than 15, tolerances to within 3 μm and surface roughness (Ra) as fine as 0.2 μm . All these values,

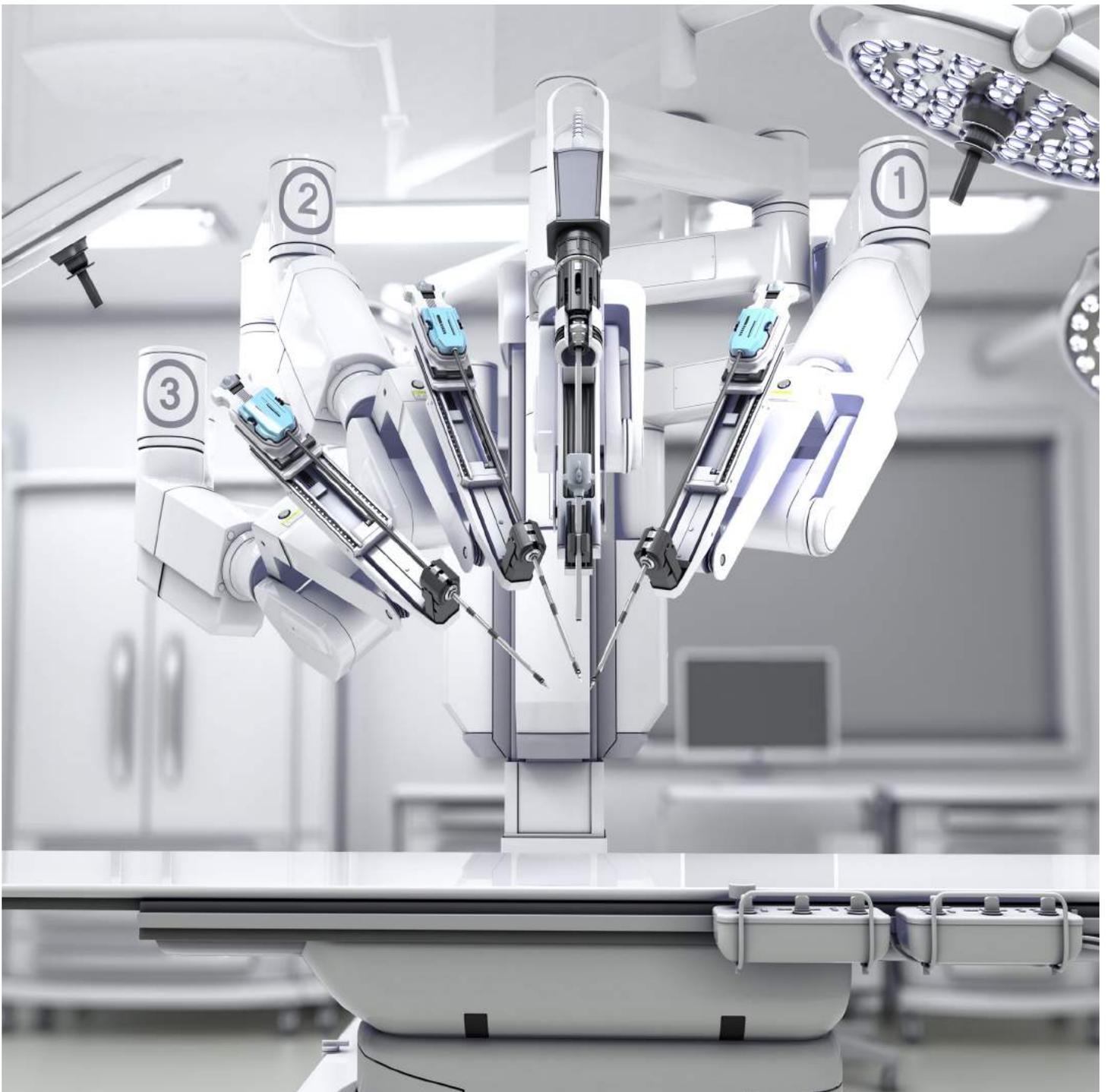
however, are influenced by the sintering process, the particle size of the ceramic powder, feedstock viscosity and powder loading [9].

PIM and CIM markets overview

In 2013, Randall M German [6] predicted two potential trends for PIM – a nearly flat growth, resulting in projected 2017 sales of around \$1.8 billion, or sustained high growth, resulting in projected 2017 sales of around \$3.9 billion. In reality, the result fell between the projections, with 2017 global PIM sales estimated at nearly \$2.6 billion. When comparing his estimated value to the actual total sales value reported on in 2017 by Georg Schlieper [10] of \$2.5 billion, with an annual growth rate of 12%, German's estimation of four years prior was surprisingly accurate.

Over the PIM industry as a whole, however, success is not uniform, with just 10% of firms controlling two-thirds of sales and enjoying 80% of the industry's profits. This inequity is important because significant changes are coming and to further grow PIM will require some changes, including improvements in production processes, application diversity and materials development [7].

From a regional perspective, the Asian PIM industry, led by China, is by far the strongest, generating about two-thirds of the world's MIM parts sales. Europe has an estimated market share of about 20%, with the US reported to hold a slightly lower level than this. Today, Europe and North America are believed to achieve approximately \$1.2 billion of combined metal and ceramic parts sales. The CIM sector represents roughly 15% of this total PIM market [10].



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Fig. 4 The starting materials for CIM feedstock preparation: organic binder and ceramic powder (Courtesy Inmatec Technologies GmbH)

Ceramic injection moulded parts are used for structural as well as for functional applications. However, it is the coloured zirconia market for aesthetic applications that has grown most strongly over the last ten or so years [11]. The production of translucent CIM parts is also a strong growth area for the industry [11].

CIM is considered to be roughly ten years behind MIM in terms of market penetration, but a more rapid development of the CIM market has nevertheless been observed. In comparison to MIM, CIM needs to create its own markets and applications and build confidence in the technology, resulting in a longer incubation time compared to MIM, where a wider range of applications can more easily be converted from competing metal processing technologies [12].

CIM feedstock: Binder systems and preparation

Since CIM, like any other ceramic shaping process, is a powder-based technology, the properties of the initial powders and the preparation of highly-particle-filled, homogeneous feedstocks that offer reproducible mould filling behaviour play a key role in process stability and the quality of the final parts. The importance of feedstock homogeneity has been highlighted by part manufacturers and researchers alike, with all agreeing that variations induced in the early process stages cannot be eliminated by the subsequent process steps of moulding, debinding and sintering. The homogeneity of the feedstock is therefore a critical characteristic for these later steps in the CIM process.

Inhomogeneities can lead to powder/binder separation, as well as defects such as cracks, voids and

part distortion, eventually leading to a failure of the manufacturing process [13,14,15,16,17]. Accordingly, a significant proportion of published papers on CIM technology deal with feedstock preparation and characterisation.

Ceramic powders

Particle size distribution, specific surface and chemical composition are the main characteristics of ceramic powders. CIM generally uses powders with particle sizes in the range of 0.2–1 μm and a specific surface area of between 5–20 m^2/g . For shrinkage control, however, these characteristics must be specified within much closer limits [18].

A smaller particle size provides a higher sintered density, but the solids loading will decrease due to agglomeration. On the other hand, a larger particle size exhibits lower interparticle friction, leading

to slumping and distortion during debinding [19]. If needed for special applications, nanopowders [20, 21] as well as ceramic powders with particle sizes of greater than 20 μm have been processed successfully into ceramic feedstock [18].

Feedstock manufacturers often complain that it is not easy to maintain consistent feedstock quality, even for standard grades, because of the variations in the characteristics of commercially available ceramic powders. This is tied to the fact that ceramic powder suppliers generally show little enthusiasm for supporting the specific requirements of the CIM industry, since production volumes are much lower than in the die pressed ceramics industry [18].

Binder systems

Process stability, as well as the quality and properties of final parts, depend on the choice of a suitable binder system [22]. The minimum requirements for binder systems include low viscosity to ensure the complete filling of mould cavities, relatively high mechanical stability to ensure safe removal from a mould, good shape retention and low shrinkage during debinding and sintering [23, 24].

All binder systems are made up of several components: a basic, low-molecular-weight binder that is easily extracted during the first phase of debinding; a backbone binder that provides strength [19] and additives such as lubricants or dispersing agents. The low-molecular-weight organic binder component acts as a plasticiser [25] between the long polymer chains of the backbone polymer to lower the feedstock's dynamic viscosity and provide the flowability required for complete cavity filling during injection of the feedstock into the mould [22].

Standard binder materials are usually based on long-chain olefines, mostly LDPE (low-density polyethylene) and short-chain waxes [22, 25, 26, 27, 28]. Each ceramic powder particle in the feedstock must be coated with the binder, but only the minimum effective amount should be used in order to achieve the required viscosity for injection moulding. The binder polymers should have low viscosity, but, at the same time, have good adhesion to the powder [29].

Feedstock preparation

The feedstock preparation process is today quite standard: the ceramic powder blend and binder system are first mixed mechanically and then plasticised and homogenised by a pair of heated shear rolls. The objective of shear roll processing is to remove agglomerates and coat each powder particle with a polymer layer so as to make injection possible and reduce abrasion in the injection moulding machine [10]. Because of the powder's fine particle size, a very strong shearing action is required to produce a high quality feedstock and the total processing time is dependent on powder properties [18, 30].



Fig. 5 Feedstock preparation with a shear roller (Courtesy Fraunhofer IKTS)

Feedstock-related research activities

Despite the higher energy input of the shear roller in comparison to a twin-screw extruder and a sigma-blade kneader, powder agglomerates cannot be completely avoided. In order to produce high solid loaded submicron and nanoparticle-containing feedstocks, Sommer *et al.* [31] suggest a pre-milling of the powders, which is effective in dispersing and deagglomerating ceramic powders.

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Fig. 6 Different CIM feedstocks and components made of black zirconia (Courtesy Inmatec Technologies GmbH)

The injection pressures needed for feedstocks from pre-milled powders were shown to be about 200 bar lower than the pressures needed for non-milled feedstocks.

During the injection moulding process, the moulding compound undergoes extremely high pressure and shear rates of up to 10^6 s^{-1} , which may lead to powder/binder segregation.

tion or non-homogeneous binder extraction during the debinding step [14, 25].

At the Universidad Carlos III, Madrid, Spain, an eco-friendly binder system for PIM, based on polyethylene glycol (PEG) and cellulose acetate butyrate (CAB), has been developed. CAB is a naturally derived product with a zero balance of CO_2 emission when degraded thermally. Mouldable feedstocks with zirconium silicate powder have been tested [32, 33].

Hausnerova *et al.* [34] developed a novel binder system in which carnauba wax (CW) and acrawax (AW) (N,N0-Ethylene Bis-stearamide) were considered to replace the synthetic backbone polymers (polyolefins) in alumina CIM feedstocks. For both proposed substitutes, there was a significant reduction in viscosity in comparison to polyolefin based binder and commercially available binders and, in the case of CW-based feedstock, there was also a significant reduction in processing temperature, which is essential for the injection moulding of reactive powders.

Most research has highlighted powder effects on rheological properties, although some research examined binder effect. Kate *et al.* [35] covered the effects of nano-particle contents on the rheological properties of bimodal feedstock. Yang *et al.* [36] studied the effect of polyethylene glycol binder with different molecular weights on rheology and found that larger molecular weight binder leads to higher yield stress and shear stress. Rheological behaviour and the mechanical properties of PMN-PZT ceramic feedstock with different binder compositions were studied for a successful complete-filling and demoulding process in micro-PIM [37].

Commercial considerations

The efforts made in feedstock research and development highlight the critical position of feedstock in the CIM process. When BASF decided to stop producing CIM feedstocks a few years ago, it became clear how



Fig. 7 Extrusion of filaments for FFF by means of a single screw extruder (Courtesy Fraunhofer IKTS)

deeply feedstock producers and CIM manufacturers are interconnected. This is, firstly, because the binder system determines the manufacturing process chain and, with it, the equipment (debinding equipment, sintering furnaces) and workflow in the factory. Secondly, the solid loading determines shrinkage and, hence, the mould scale and dimensions of the final component.

Generally, a decision has to be made by CIM manufacturers as to whether to purchase feedstock or to produce it in-house. The latter is often chosen when specific needs have to be fulfilled (e.g. specific powder mixtures).

Nevertheless, commercial feedstock producers serving the market often supply customer-specific feedstocks in addition to their standard materials.

Some commercial CIM feedstock providers offer feedstocks manufactured from a range of binder systems. As an example, INMATEC Technologies GmbH, Rheinbach, Germany, offers three standard types of binder system: one is based on wax-polymer and suitable for partial debinding in water; another, based on polyamide, requires partial debinding in acetone; the third is based on polyoxymethylene (POM) and requires catalytic debinding in a nitric acid environment [10].

Recently, interest has also grown among ceramic powder producers in manufacturing their own feedstocks. For example, zirconia feedstocks are available from Tosoh, Japan, and Saint Gobain, France. AlzChem, Germany, provides silicon nitride feedstock.

CIM feedstocks for Additive Manufacturing

PIM feedstocks are not only suitable for Powder Injection Moulding, but also for Material Extrusion (MEX) Additive Manufacturing processes such as Fused Filament Fabrication (FFF). The extrusion process is capable of generating complex profiles with very thin wall thicknesses in a range of materials. FFF has been evaluated for the production of prototypes and small series of ceramic components using flexible thermoplastic filaments basing on CIM feedstocks that can be coiled and 'printed' like plastic filaments on low-cost machines. The resulting green parts are machinable by milling, as commonly performed on CIM green parts, and the debinding and sintering steps are identical.

The challenges of tooling

Tooling is perhaps the most expensive and time-consuming step in a CIM part's development. Two main trends can be identified in this area: one trend goes in the direction of low-cost moulds, whilst the other is towards high-performance tools.

The low-cost route

Low-cost moulds can either be made using cheaper materials, or 'lost' tool inserts can be created by Additive Manufacturing [38]. Low-volume and prototype parts are

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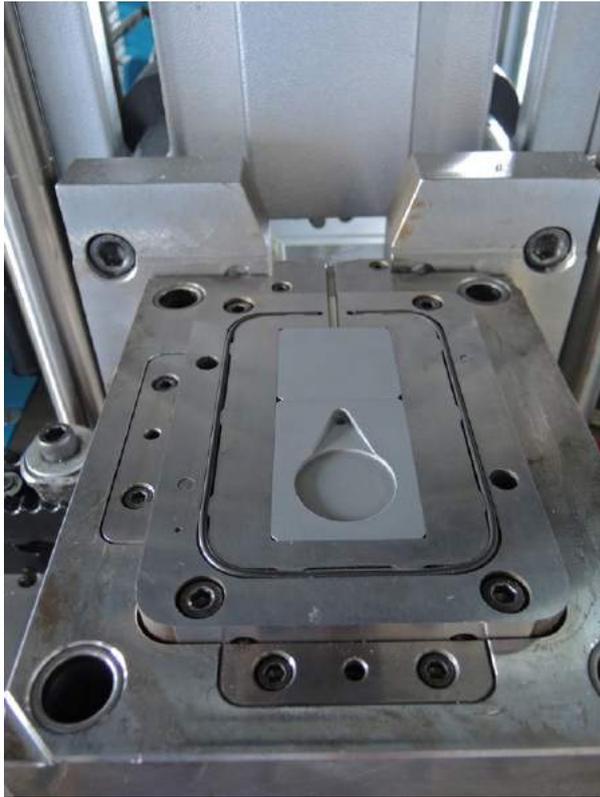


Fig. 8 Ceramic tool insert made of Si₃N₄ for avoidance of iron impurities resulting from tool abrasion [Courtesy Fraunhofer IKTS]



Fig. 9 Demonstration frame for a mobile phone made by MIM showing the potential for PIM parts with high aspect ratios [Courtesy Arburg GmbH]

often made first from single-cavity aluminium tooling; such tooling can last for up to 10,000 cycles and cost far less than the tool steel equivalent [39].

Lost mould inserts are interesting for manufacturing extremely complex-shaped or individualised components without mould parting planes and can be used for low-volume or single-piece production. This is a territory that so far has primarily been occupied by AM.

Advanced tool design and production

The opposite trend to low-cost or single-use moulds focuses on highly sophisticated and optimised tools for improved mould filling behaviour, improved surface quality of the injection moulded parts and optimised cycle time.

PIM processes have, in the past, typically relied on an isothermal, or constant, mould temperature to produce parts. Since this tempera-

ture is considerably lower than the melting point of the feedstock material, high injection speeds are required. Without these higher speeds, adequate filling of the cavities cannot be achieved before the premature freezing of the feedstock material.

Accordingly, a new approach is for the mould temperature to be brought up to the melting point of the feedstock in a controlled manner during each injection cycle. Variotherm temperature control systems are now being used as the basis for dynamic mould temperature control in PIM. By switching between defined temperatures, the user can directly influence the surface flow and the solidification behaviour of the feedstock [40]. A further advantage of variothermal temperature control becomes obvious when the available injection pressure of the injection moulding machine would be insufficient to completely fill an isothermally-

tempered mould of a thin-walled part [39]. Ultimately, as PIM parts become larger and ever more complex, this system guarantees the highest possible part quality for the final product, with maximum reproducibility.

A trend towards multi-cavity moulds

There is currently also a noticeable trend towards the use of multiple cavities in Powder Injection Moulding production. When it comes to incorporating multiple cavities in a PIM tool, it is essential that the route of the runner to each cavity is of equal length [41]. The sprue and runner must therefore be branched accordingly. To guarantee this parameter, Arburg GmbH, Lossburg, Germany, has reported on the use of a temperature-controlled, liquid-based hot runner system: stable temperature control, it stated, cannot be sufficiently guaranteed using electric hot runners [39].

A commercial example of this trend is in the production of ceramic burner components for HID lamps at Philips' Uden plant in the Netherlands. Here, multiple cavities and hot runners are standard and the number of cavities has been continuously increased from a single-cavity to over eight per mould. The injection moulding process is monitored by temperature sensors in each cavity and the hot nozzle temperature is adjusted on each gate separately.

Feedstock viscosity, which is affected by temperature, is therefore controlled to ensure that all mould cavities are uniformly filled [42, 43].

Mould filling simulation

Simulating the flow of PIM feedstocks can help to anticipate possible moulding defects at the start of the tool design process, enabling them to be corrected prior to the actual mould being manufactured. Additionally, simulation can help to improve mould filling. The thermal balance of the mould and heat flow is of prime importance for efficient injection moulding. A simulation model must cover all heat-relevant parts of the mould, including their thermophysical properties and the heat transfer between neighbouring parts [10].

Process simulations are based on the Finite Element Analysis (FEA) method, and a number of commercial packages are available on the market, including Autodesk Moldflow®, Moldex3D® and Sigmasoft®. However, the simulation software developed to date for PIM originates from the injection moulding of plastic feedstock and there are limited data to enable the simulation of PIM feedstocks where, of course, the material being injected comprises a mixture of a binder and ceramic or metal powder. Such PIM feedstocks have significantly different properties to pure or even filled plastics.

One of the reasons why there are almost no material data, and no material models of feedstocks widely available, is because there are no 'standard' feedstocks, but rather a wide variety of binder types that are

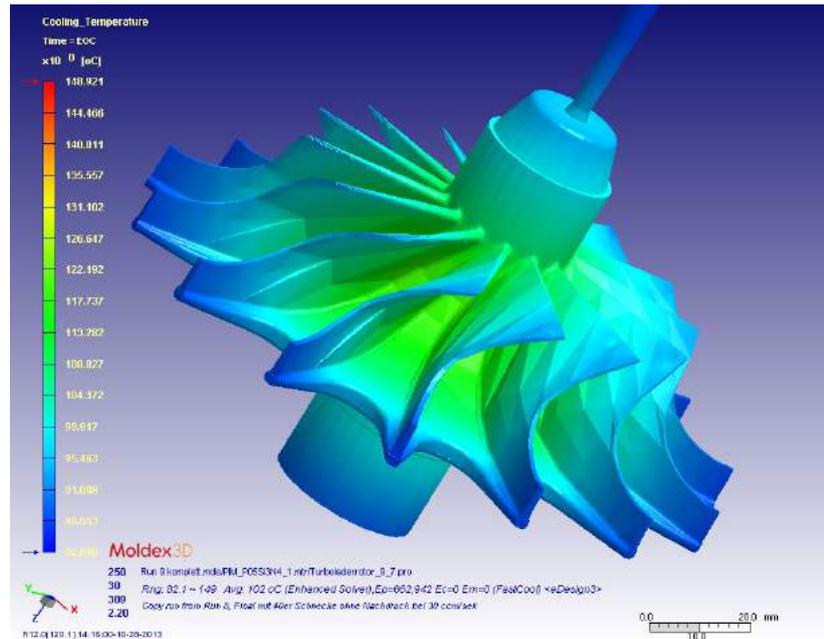


Fig. 10 Simulation result of the cooling behaviour of an injection moulded micro turbine impeller (Courtesy Fraunhofer IKTS)

mixed with an even greater variety of powder types. Additionally, guidelines or standards for the acquisition of such material data, or for the application of simulations, do not yet exist.

Attempts have been made to describe the behaviour of PIM feedstock analytically, which shows promising results [44], and some material studies on feedstocks have been reported in recent years. Still, almost all of these investigations focus on a limited selection of material properties – mostly either on the rheological or thermal aspects [45, 46, 47].

A collaborative research project, undertaken at the Technical University of Denmark, the University of Applied Sciences Northwestern Switzerland and Germany's Karlsruhe Institute of Technology, focused on a broad and comprehensive characterisation of two ceramic feedstocks, with the material data obtained potentially allowing the development of material models for the simulation of mould filling during injection moulding [48].

Simulation tools for multicomponent plastic injection moulding have been extended by developing a 2C-PIM simultaneous simulation.

A comparison of simulation and experimental results shows promise. In 2C-PIM, the sintering step involves high temperatures, holding times, diffusivity and, consequently, the interdiffusion of alloying elements and phase formation, which are essential aspects for the interface of materials with differing chemical compositions [49]. The effect of various heating rates and the orientation of the parts in relation to the heat source on temperature gradients in the furnace load has also been studied by computer simulation [10].

The debinding process

Following the actual shaping process by injection moulding, a processing step intrinsic to PIM is the removal of the organic binder system immediately before densification of a component is carried out by sintering. The debinding step must be performed very carefully to avoid common failures such as distortion, the formation of cavities, or surface defects.

The debinding process can be time consuming – up to several days depending on the binder constituents and particle size of the ceramic

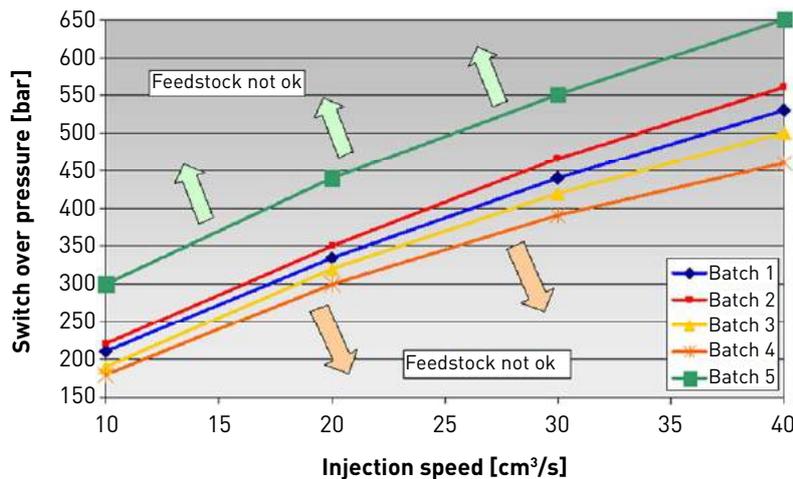


Fig. 11 Curves which are created with Arburg's feedstock test (Courtesy Arburg GmbH + Co KG)

powder. Debinding time is closely connected to the level of porosity in the component: the higher the porosity, the easier the diffusion of the decomposed binder from deep inside a part to the surface.

There are four major debinding approaches applied in Ceramic Injection Moulding: thermal debinding, partial solvent debinding followed by thermal debinding, partial water debinding followed by thermal debinding [50] and catalytic debinding [51, 52, 53]. For Low Pressure Ceramic Injection Moulding (LP-CIM) feedstocks, which contain wax as one constituent of the binder system, wicking of molten wax using a porous powder bed is an established process. For thermal debinding, the process is time consuming because the debinding rate has to be slow in order to avoid internal pressure build-up from gas released by the decomposing binder, which can cause cracking and blistering [54].

Solvent debinding

Depending on the binder composition, solvent debinding can be performed in water or in an organic solvent. The purpose of solvent debinding is to remove the first stage binder and to create a network of open porosity in the CIM compacts. This will allow the evaporating backbone binder to escape during later thermal debinding without causing the internal pressures that might destroy the parts.

The time and temperatures required for solvent debinding depend on the wall thickness of the parts and the particle size of the powder used. Simon *et al.* describe the water debinding step for the optimisation of feedstock formulations and the shortening of processing time [55]. Solvent debinding can significantly reduce debinding times and greatly improve productivity [53].

Suitable solvents depend on the employed binder system: for PE-wax binder, n-hexane is a typical solvent, whereas, for PA-based binders, acetone and ethanol can be used [56], Williams mentions further trichloroethane or heptane as solvents [57]. Liu *et al.* adopted low-toxicity, low-cost kerosene as organic solvent to study the solvent debinding behaviour of green zirconia bodies containing PW, HDPE, PP and SA as binder constituents [58]. The solvent bath is usually heated from 25 to 60°C in order to accelerate the diffusion processes.

Thermal debinding

For thermal debinding, heating ramps and dwell times may differ not only for different binder systems, but also for different powders [18]. For organic solvent debinding, the organic solvents are mostly flammable, carcinogenic and not environmentally acceptable. At the industrial scale, debinding equipment is available that works in a closed loop and captures/recycles solvent by distillation.

Water debinding

In contrast, partial water debinding followed by rapid thermal pyrolysis, with its high efficiency and environmental acceptability, has emerged as a good alternative [57, 59]. For this approach, the water-soluble binder is firstly removed as the interconnected pore channels are formed from the exterior to the interior. Insoluble binders remain in the contact region between the powder particles, with the pore channels serving as escape paths for decomposed gas during the subsequent thermal debinding for insoluble binders. PEG/PMMA (polyethylene glycol/poly methyl methacrylate) binder systems are among the most widely used water-soluble binders for CIM [49].

Significant progress has been made in debinding technology in recent years; in addition to the catalytic debinding approach originally developed by BASF SE, which offered excellent performance in terms of extremely short debinding times, thermal debinding and solvent debinding are now widely used [50]. It should be noted that innovation in this area has in large part been driven by the demand for CIM components from the luxury watch industry, where an interest in technological innovation and environmental responsibility go hand in hand.

Testing and quality management for CIM materials

For component manufacturers delivering parts for the automotive industry, Quality Management systems certified according to ISO TS 16949 are standard. A large amount of processing parameter data is recorded electronically and continuously; other data are typed into the system by the operators. When it comes to CIM materials, there are some specific areas that should be highlighted.

Powder testing

The most important test during the incoming inspection of powder is the weight loss of the powders by annealing in air at 1025°C, according to ISO 26845. The weight loss determines the content of organic substances and humidity in the powder. After feedstock production, the weight loss of the feedstock is measured for a reverse cross-checking of the powder-binder ratio. Each feedstock batch is injected with reference parameters into a standard mould to monitor batch-to-batch consistency. Injection moulded parts are also retained as reference samples [18].

Feedstock testing

The homogeneity of feedstocks can be determined by measuring the variation in density using a gas pycnometer [60]. Low variations in densities show that binder system and powders are homogeneously mixed through the compounding process. With the average measured density of powders and binder system, the volume fraction of powder can be determined using the rule of mixture.

Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) have been used to determine the powder distribution and segregation of silicon nitride powder within injection moulded test bars [61]. With the TGA experiments, the powder content in the feedstock or test bar is determined by the remaining weight fraction of specimens.

According to Walcher *et al.* [62], a constant feedstock viscosity is key for PIM component quality and reproducibility. To address this, an alternative method for feedstock validation on a real injection moulding machine by measuring the flow behaviour has been developed. In this method, the maximum injection pressure at the switching point to the holding pressure in an injection moulding machine working under thermal equilibrium conditions is deliberately estimated. The testing tool used produces parts while the tool cavity is filled to less than 100% with different injection speeds. The machine

control registers the pressure at switchover point. From the pressure values, information about feedstock quality can be extracted which can be applied directly to an injection moulding machine's process parameters (see Fig. 11).

The most common method, widely applied in industry, is to analyse the melt progression by producing a short shot study [63, 64, 65]. By interrupting the injection process at different points, a sequence of filling stages is created. The obvious advantage is its universal applicability to all tools using normal production conditions. Furthermore, it requires only modest time and cost. However, the produced samples show only the state at one moment and do not reflect the flow pattern in the final part.

In order to investigate flow behaviour experimentally, several approaches have been developed to visualise the flow pattern. They follow approaches such as direct melt observation, evaluating surface marks, introducing tracer particles into the melt and interrupting the injection process. For direct observation, the melt flow is recorded inside the mould by high-speed cameras. Special tools need to be applied in which one cavity wall is substituted by a transparent window to allow connecting of the camera [66].

Powder/binder separation

For detecting binder separation within the injection moulded bulk material and at the joining zones of two-component parts, the microstructures of green samples have

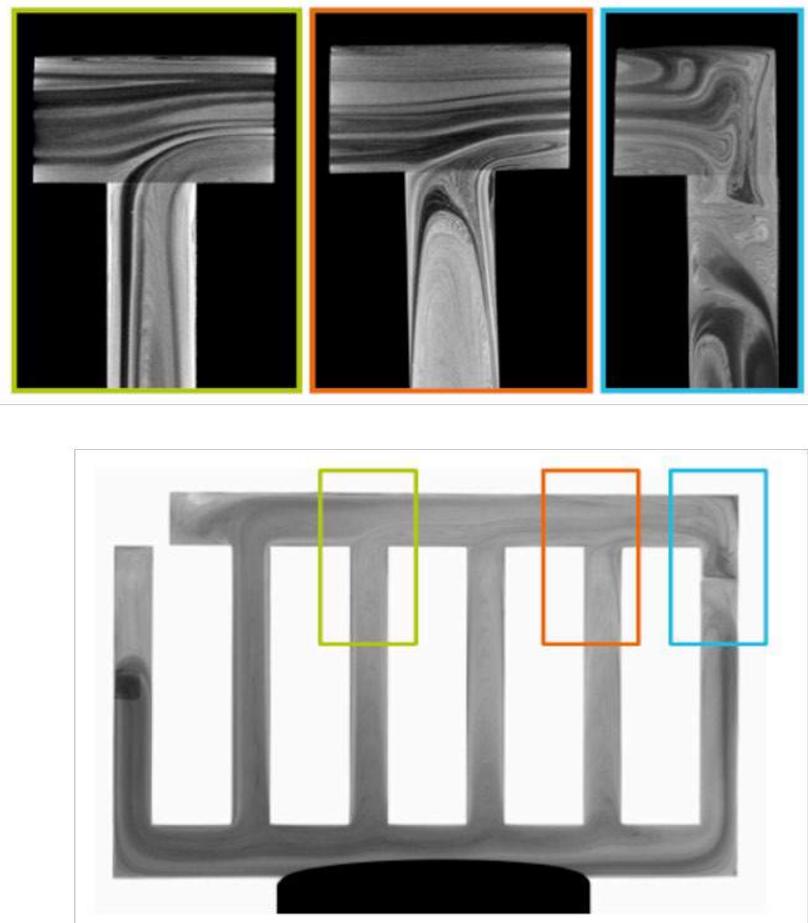


Fig. 12 Radiographic image of an injection moulded test part. The flow lines of the feedstock are visualised by means of a so-called tracer feedstock (Courtesy Fraunhofer IKTS)

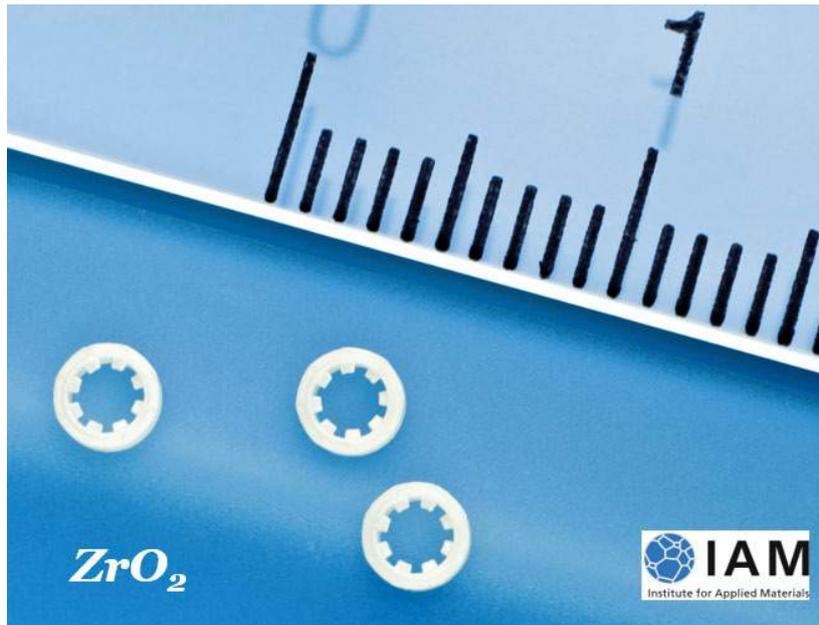


Fig. 13 MicroCIM parts made of zirconia [Courtesy KIT-IAM]

been studied. Since conventional machining processes such as grinding and polishing modify the original structure, for example when particles are pulled out of the binder matrix and smeared onto the surface, a special ceramographic method for the preparation of cross-sections was applied.

This approach, developed by Mannschatz *et al.*, is based on broad ion beam techniques and enables the simultaneous polishing of hard ceramic particles and soft polymer molecules without destroying the structure or producing protrusions on the surface [67]. In the analysed samples, binder accumulations were found along flow lines, at weld lines, at the boundaries of so-called dead water regions and at the interface of two-component parts.

A further visualisation method is introduced using a tracer material which can be detected by X-ray computed tomography [68]. A marker material feedstock that differs in X-ray attenuation, but has the same flow behaviour, is added to the base feedstock during the moulding process. Due to inhomogeneous mixing, the flow pattern becomes visible in CT scans (see Fig. 12).

CIM process variants

MicroCIM

As a near-net shape technology, micro-Powder Injection Moulding (MicroPIM, or MicroCIM in the case of ceramics) is characterised by low cost, high precision and high efficiency [69, 70, 71]. It can produce parts with complex shapes on a large scale and can be used to make ceramic parts with micro-holes. In particular, it has significant advantages in the production of ceramic array micro-holes.

As a common and widely used type of micro-feature, micro-holes act as transfer and exchange media in the form of micro-channels or nozzles that can be used as fuel injection nozzles, spinnerets, jet turbine blade cooling holes, printer jets, micro-structures for an array hole in a micro-pump and micro-hole structures in fibre optic connectors and biomedical filters [72, 73, 74, 75].

Wang demonstrated the capability of MicroCIM in fabricating thin multilayer microparts with microstructures [76]. A part with microchannels and microholes was designed and fabricated

through the integration of UV-LIGA, MicroCIM and variothermal mould temperature control technologies.

Micro-powder in-mould labelling

Micro-powder in-mould labelling (MicroIML) is a variant of macroscopic in-mould labelling. It is capable of applying a functional material on the surface of a MicroPIM part of complex geometry. For this approach, a thin ceramic or metallic green tape, made by tape casting, is inserted into the cavity of the injection moulding tool. Next, the ceramic or metallic feedstock is injected and combined with the green tape by using the applied injection pressure of the feedstock and by a certain inner tool surface microstructure [77, 78]. After debinding and sintering, the functional material is firmly connected with the substrate material [79].

UV-assisted nanoimprint lithography

Mühlberger demonstrates the successful replication of biological surface structures, specifically the surface of the ventral snakeskin, onto foils using UV-assisted nanoimprint lithography (NIL) [80]. Such parts are used, for example, in production equipment for components with a high friction load, and nanostructured ceramic surfaces may play an important role for MEMS, smart surfaces, sensorics and other intelligent components.

Sintered magnetic materials

Drummer *et al.* describe the MagnetPIM process, which combines the advantages of sintered magnetic materials with injection moulding to produce magnetic components with highly complex geometries [81]. In this process, the binder system is mixed with magnetic particles. In the case of anisotropic particles of magnetically hard materials, these particles can be oriented during the injection step by a three-dimensional magnetic field applied to the injection moulding tool. This enables the manufacture of complex multi-polar components.

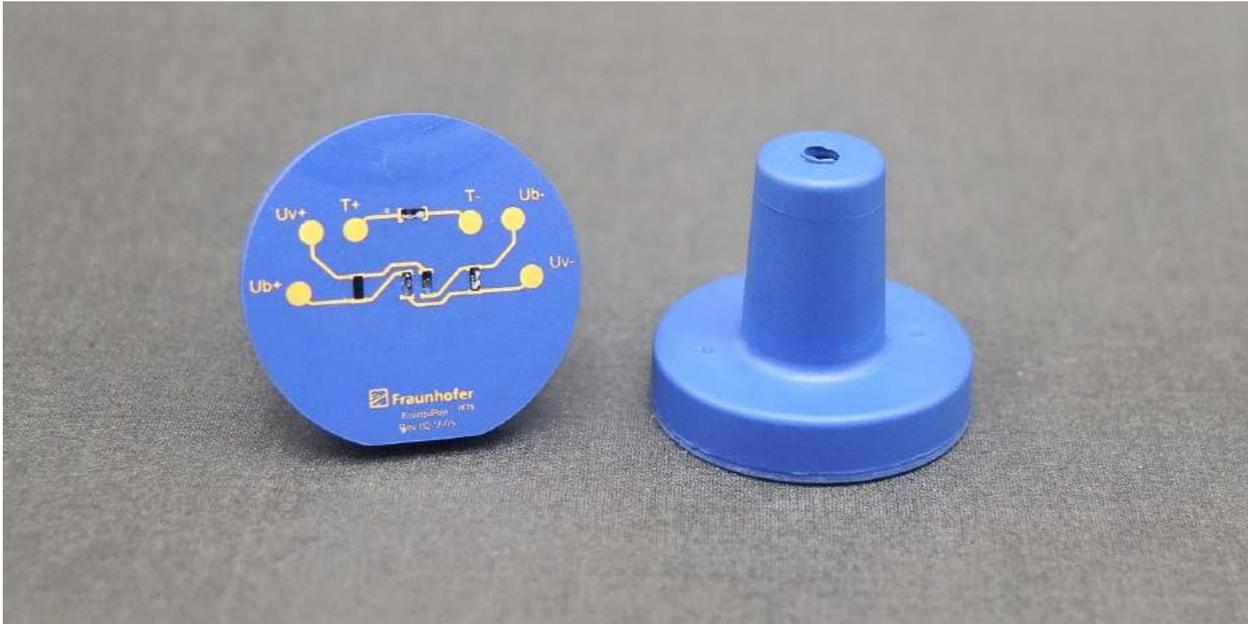


Fig. 14 LTCC pressure sensor made by Inmould Labelling (Courtesy Fraunhofer IKTS) [91]

Combining Ceramic Multilayer Technology & CIM

According to Ziesche, an observed trend in circuit board technology is an increase in geometrical complexity combined with an increased functionality [82]. For the manufacturing of novel functional ceramic components, Ceramic Multilayer Technology (MLC) has been combined with CIM [82]. For this application, low-temperature co-fired ceramic (LTCC) dielectric base material was tape cast. The LTCC powder was mixed with the same organic binder components used as binder for the tape and an injection moulding feedstock prepared. To

generate even more geometric flexibility, a sacrificial material was used to create embedded undercuts or channels by the injection of a lost core. The best results were achieved with polyoxymethylene (POM), which was removed before the ceramic firing process by thermal extraction.

The manufacturing process consisted of several steps. Firstly, the LTCC-multilayer laminate was inserted into the injection moulding tool. Then the lost core, which creates the pressure chamber after the sintering process, was injected. In the third step, the LTCC media port was injected around the lost core and upon the LTCC-laminate.

The lost core was then extracted and the ceramic component debound and fired to form a monolithic ceramic component (Fig. 14) [83].

Ceramic materials processed by CIM

Early successful ceramic materials for CIM were oxide ceramics, notably alumina, which remains a mainstay for the Ceramic Injection Moulding industry [7]. By the late 1980s, the main focus was on oxides, alumina, silica and zirconia, with some efforts in silicon nitride and silicon carbide.

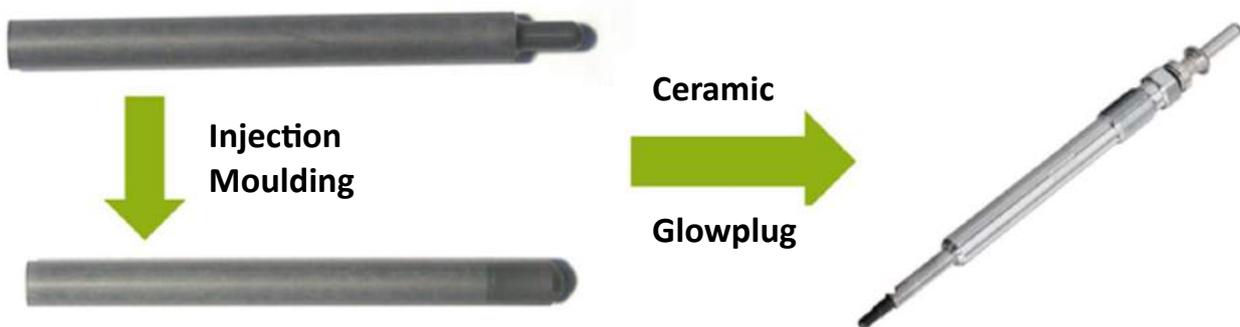


Fig. 15 Ceramic glowplug made of electrically insulating and conductive silicon nitride by multi-component injection moulding (Courtesy BorgWarner)



Fig. 16 Internal screw thread in an alumina part made by CIM (Courtesy Kläger Spritzguss GmbH)



Fig. 17 Needle component made of alumina (Courtesy Kläger Spritzguss GmbH)

The demand for zirconia CIM products is currently growing significantly in the consumer electronics market, whilst there are an increasing number of applications for alumina in the automotive sector and the consumer products market.

A growing demand is also being seen for silicon nitride and translucent ceramics. Other engineering ceramics, such as silicon carbide and boron nitride, are available, but demand remains limited [10].

Currently, one of the most widely used materials for structural

applications in medical technology is alumina. In the future, many more applications for functional ceramics are expected to develop in medical technology for innovative methods of surgical interventions, medical diagnostics therapy and patient monitoring. Polycrystalline alumina (PCA) has the potential to replace sapphire at less than one fifth of the actual cost. It is free from contamination, completely inert, scratch-proof and corrosion resistant. It also combines extremely high hardness, heat resistance, high

thermal conductivity and electrical insulation [42].

Materials R&D activities

Over the past decade, many papers have been published, which report on the processing of new materials by CIM.

- As previously mentioned, Drummer *et al.* used injection moulding for the manufacturing of complex-shaped magnetically hard components consisting of $\text{SrFe}_{12}\text{O}_{19}$ [81, 84].
- Thermoplastic forming of alumina-SiC nanocomposites has been carried out by Kern *et al.* [85].
- Liu *et al.* developed a method for doping zirconia preforms by infiltration of debound injection moulded green bodies with ion solutions, which resulted in coloured zirconia components [86, 87].
- Zhang *et al.* manufactured Reaction-Bonded Silicon Carbide (RBSC) by CIM using feedstocks containing silicon carbide, carbon black and paraffin wax, HDPE, EVA and stearic acid as organic binder system [88].
- Functional ceramic components made of piezoelectric PMN-PZT have been produced by Han *et al.* [89].
- PIM has been used to produce complex-shaped samples with a high reproducibility of MAX phase Ti_3SiC_2 powders [90]. MAX phases combine typical metal and ceramic properties, such as high rigidity, good mechanical properties at high temperatures, high resistance to corrosion and oxidation and good thermal and electrical conductivity.
- Böttcher *et al.* describe the injection moulding of Oxide Ceramic Matrix Composites (OCMC) by means of alumina and alumina fibres (Nextel 610) [91].
- Tülümen and Piötter used alumina and chopped alumina fibres for producing fibre rein-

forced oxide ceramics by CIM [92, 93].

- Pre-ceramic polymers were used as organic vehicle forming a ceramic matrix after pyrolysis [94, 95]. Carbon short fibres were chosen as the fibre material. The Ceramic Matrix Composite (CMC) is formed by pyrolysis of the polysilazane precursor with an amorphous Si-C-N network as the matrix for the short-fibres.

Glass components by CIM

Ceramic Injection Moulding has also been successfully developed for the manufacture of sintered glass components. Since conventional glass components are usually shaped from a melt by blowing, drawing, rolling, or casting, this does not only imply high temperatures, but also limitations for structural details. Achieving structures such as well-defined channels therefore requires mechanical machining or chemical etching.

Manufacturing glass components by a powder-based route has advantages: sintering is conducted above the transition temperature of glass, but well below the molten state, which in turn saves energy. Functional glass matrix composites can be realised by adding particulate additives, which are not affected by



Fig. 18 Microstructured testing bars made of sintered coloured glass by CIM (Courtesy Fraunhofer IKTS)

side reactions with the glass melt, as the glass viscosity required for sintering is lower than for melting. This increases the opportunities for possible composite combinations and allows for a wide range of secondary phases.

Several publications have reported on conductive and insulating glass-based composites, combined by applying 2C-PIM [96, 97, 98, 99]. A borosilicate glass was used as a matrix material. The conductive component is a

glass-graphite- composite based on the same glass. The carbon species is incorporated into the glass matrix and forms a network of conductive particles; above the percolation threshold, electrical current can flow through the touching particles and, due to ohmic losses, heat is produced. This principle is the basis for its application as a heating device (Fig. 19). In the work of Enríquez *et al.*, CIM is used to process rare earth-free glass-ceramics with photoluminescent properties [100].

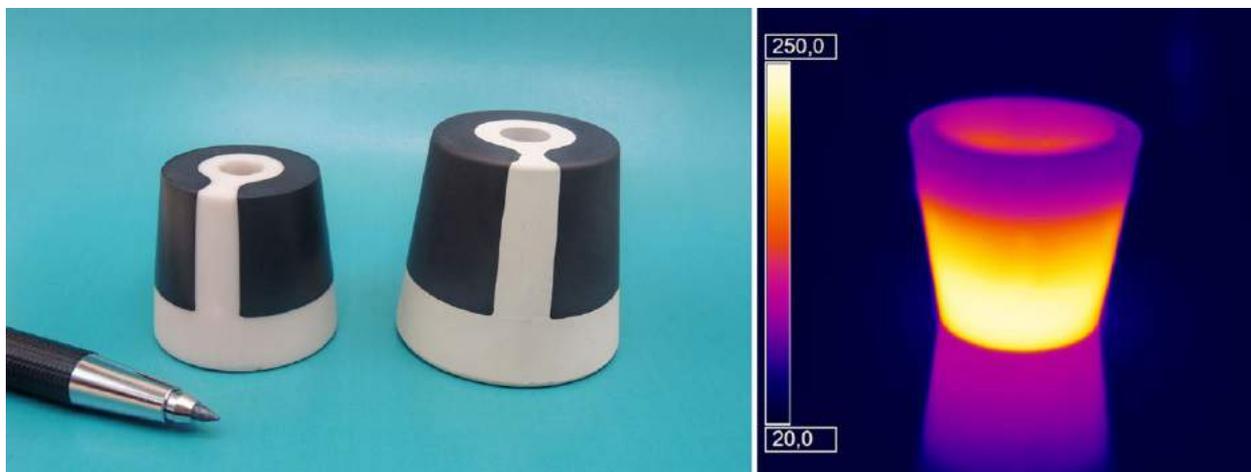


Fig. 19 A two-component glass component with intrinsic heating element (left) and an IR camera image of the component during heating (Courtesy Fraunhofer IKTS)



Fig. 20 Watch components made of translucent alumina (Courtesy Fraunhofer IKTS, Inmatec Technologies GmbH)

CIM applications

Tables 1–6 detail a range of CIM applications that have been recorded across a number of industry sectors. Several major CIM applications can be regarded as having long lifespans, remaining in production for ten to twenty years with only minor changes. Examples include:

- Aerospace (casting cores, inlets, nozzles, linkages)

- Medical/dental (surgical tools, brackets, implants)
- Industrial (housing, pumps, fittings, locks).

Applications in smartphones, home appliances, wearable devices and other products sometimes land with a splash, but within months are gone [7].

Swiss producers of luxury watches have expanded their market with new shapes and designs and the

automotive industry is also looking for new aesthetic applications for luxury interiors.

CIM zirconium oxide was first developed for luxury watchcases and bracelet segments in the mid-1980s by Rado Watches of Lengnau, Switzerland, and IWC Schaffhausen, Switzerland. Recent years have seen an increasing number of leading luxury watchmakers embracing CIM for watchcases, bezels, bracelet segments and even movement parts, adding a significant premium to their already successful metal-based timepieces [101].

CIM watch components are produced primarily using ultrafine tetragonal zirconia powders, although other types of ceramic powders such as silicon nitride, titanium nitride and boron carbide have been introduced. Black zirconia parts have become standard for many CIM watches, but a number of higher-end watch producers are now turning their attention to incorporating other colours [97].

In the medical sector, the biocompatibility of ceramics is a tremendous advantage, as are the thermal/ electrical insulating properties of



Fig. 21 Variety of DENSILOX® Ceramic Dental Solutions (Courtesy CeramTec GmbH, CC BY-ND 3.0 DE)

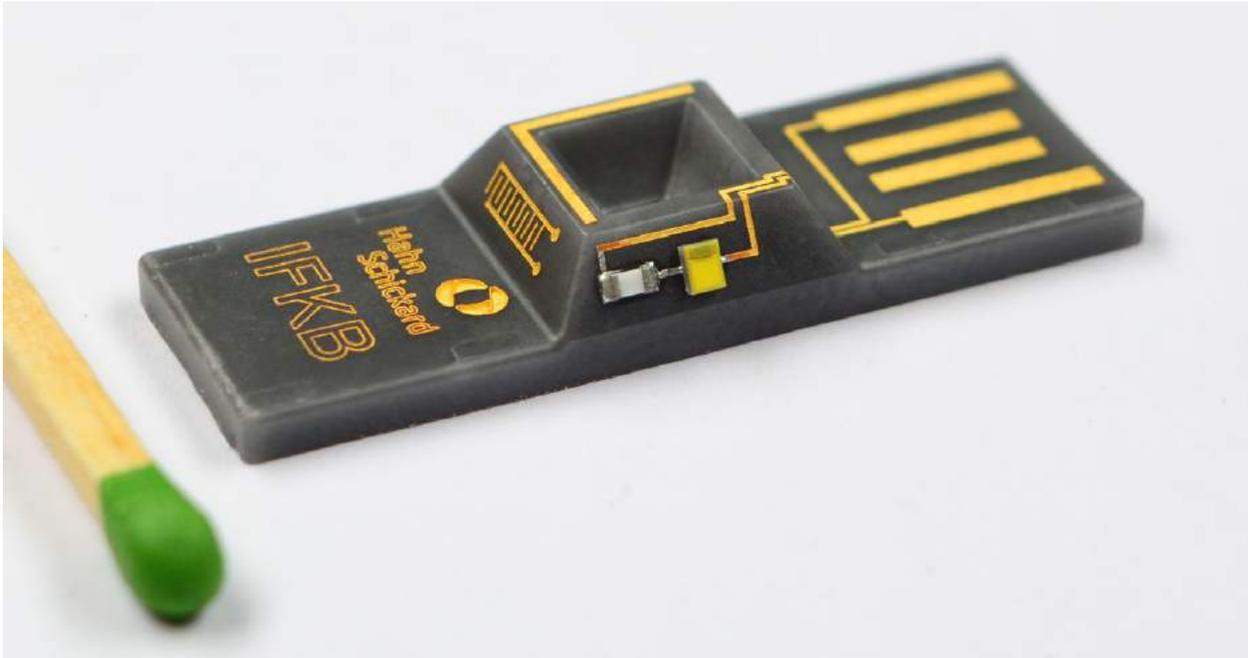


Fig. 22 An alumina CIM component sintered in hydrogen, equipped with conductive paths, series resistor and LED, three-dimensionally structured by Direct Laser Structuring (Courtesy Hahn Schickard and IFKB, University of Stuttgart)

CIM materials, offering the ability to isolate heat sources at the tip of medical devices and thereby reduce the risk of injury to patients.

In the aerospace industry, ceramics provide significant compressive strength; high wear and low coefficient of friction for parts

that rotate against one another, such as hub bushings; and their extreme heat resistance makes them suitable for engine applications. There are also opportunities for the use of ceramics in aggressive environments such as jet fuel systems [102].

Whilst hybrid vehicles and computer servers are today leading high-volume applications for Ceramic Injection Moulding, high-intensity, solid-state lighting is also becoming a 'mega market' for ceramic heat dissipation applications [7].

MEDICAL/DENTAL APPLICATIONS	Material	References
Osteo-inductive parts for bone substitution	Calcium-phosphate powders with an adding of bioactive glasses	[104]
Biomaterial with good biological and mechanical properties	Titanium alloy Ti6Al4V and hydroxyapatite	[105], [106]
Translucent orthodontic brackets	Polycrystalline alumina (PCA)	[7], [107], [108]
Abutment for implants	Zirconia	[103], [104], [109], [110]
Dental implants	Yttria-stabilised zirconia	[10], [111]
Dental drills, scalpels, tweezers	Zirconia	[106]
Hip implants	Zirconia-toughened alumina (ZTA), platelet reinforced ZTA	[112]
Feedthroughs for hearing implants	Alumina	[113]
Screws for fixing implants to the bone	Alumina	[18]
Tools for micro-invasive surgery	Alumina, zirconia	[7], [18], [98]
Heart pacemaker bodies	Alumina	[7]

Table 1 Examples of CIM parts in the medical and dental sectors

AEROSPACE, DEFENCE AND AUTOMOTIVE	Material	References
Nozzles		[7]
Jet fuel systems		[98]
Casting cores	Porous alumina	[7]
Sound navigation and ranging (SONAR) system	Lead zirconate titanate (PZT) /polymer composite	[36], [86], [117], [118]
Automotive lighting (HID lamps)	Polycrystalline alumina (PCA)	[42]
Glow plug for diesel engines	Si ₃ N ₄ -SiC-MoSi ₂ composites	[11], [114]
Sliding shoe for controllable automotive water pumps	High-performance Si ₃ N ₄	[115]
Automotive interiors	Black zirconia	[116]

Table 2 Examples of CIM parts in aerospace, defence and automotive

CONSUMER ELECTRONICS & COMMUNICATIONS	Material	References
Positive thermal coefficient (PTC) elements for battery powered devices and heating elements for glue guns	Titanates	[11], [18]
Components for dot-matrix printers	Alumina	[103]
Bluetooth and sensor-containing jewellery with integrated health indicators	Zirconia	[120]
Ceramic bodies, frames, buttons, and plugs for cellular telephones for better phone reception and lighter devices	Zirconia	[7], [103]

Table 3 Examples of CIM parts in consumer electronics & communications

WATCHES, JEWELLERY & LUXURY GOODS	Material	References
Scratch-proof watch glass	Polycrystalline alumina (PCA)	[42]
Translucent watch cases	Polycrystalline alumina (PCA)	[121]
Luggage buckles, logos	Zirconia	[7]
Watch cases, bezels	Black zirconia, Si ₃ N ₄ , B ₄ C, tin, coloured ceramics	[97], [103]
Bracelet segments	Zirconia, Si ₃ N ₄	[97]
Rotors and tourbillions	Zirconia	[97]
Ceramic ball bearings for the barrel	Zirconia	[97]
Jewellery rings	Zirconia	[97]

Table 4 Examples of CIM parts in watches, jewellery and luxury goods

METAL FORMING / CASTING CORES	Material	References
Temperature sensor for steel melts	Si ₃ N ₄ -SiC-MoSi ₂ composites	[92], [93], [122]
Oxygen sensors for steel melt	Zirconia	Heraeus Electro-Nite, Belgium
Pouring spouts	Ceramic refractories	[7]
Filters	Ceramic refractories	[7]
Crucibles	Ceramic refractories	[7]
Casting cores for turbine components	Porous alumina	[7]

Table 5 CIM parts in metal forming technologies

GENERAL ENGINEERING AND OTHER APPLICATION AREAS	Material	References
Cutting tool inserts	WC-10%Co cemented carbide	[103], [123]
Wood-cutting tools	Alumina	[124]
Wear resistant components	Alumina in a matrix of WC-Co, tool steel with reinforcing tic	[7]
Bearings, balls	Si ₃ N ₄	[4], [125]
Electrical discharge machinable ceramics	Zirconia based ceramics with addition of different amounts of titanium carbide as electrically conductive phase	[126]
Housings		[7]
Pumps		[7]
Fittings and locks		[7]
Complex ceramic acoustic reflectors used in ultrasonic flow meters		[127]
Ceramic clevis sensor housing for online substance concentration measurements in pipelines	Zirconia	[128]
Electrical components		
Functional gradient heat sinks	AlN/copper, high-heat radiating alumina	[7], [119]
Temperature sensors	High-thermal emittance alumina	[111]
Food/Beverage industry		
Grinders for salt and pepper mills and grinding discs for coffee machines	Alumina, ZTA, zirconia	[18], [129]
Needles for piercing of coffee pods	Alumina	[18], [119]
Rotary nozzles for high-pressure cleaners	Alumina, ZTA, zirconia	[119]
Tableware	Alumina-rich porcelain	[116]
Optical components		
Scratch-proof lenses	Polycrystalline alumina (PCA)	[42]
LED parts	High heat radiating alumina	[111]
Light reflecting ceramic parts	Fine-grained 99.99% purity translucent alumina	[111]
Power generation / storage		
Porous anode support for SOFC	Nio-YSZ	[10], [130], [131]
Axial turbine rotors for electrical generators	Si ₃ N ₄	[132], [133], [134]
Recuperators	Si ₃ N ₄	[128]

Table 6 Examples of CIM parts in general engineering and other application areas

According to Nier, for the production of C/C-SiC brake discs via the liquid silicon infiltration method (LSI), the overall cost can be reduced by implementing an injection moulding process, as the hot pressing process, which is the current 'state of the art' for the shaping of the CFRP composites, consists of several manual steps,

which increase production cost [103].

The continuously increasing need for electronic parts in the automotive industry as it moves towards electrification, coupled with miniaturisation and reduction of powder consumption, is expected to lead to a further acceleration of growth in the CIM industry beyond 2020 [11].

Increasing demand is expected for refractory materials, for example in rocket nozzles, engines and armour. Additionally, the use of PIM within the medical device industry looks set to rise as the demand for multi-scale components with micro-patterns, made out of biocompatible materials, increases.



Fig. 23 Exhaust gas sensor made of alumina (Courtesy Formatec B.V.)

Trends in Ceramic Injection Moulding

Larger parts with higher aspect ratios

In recent years, there has been growing interest in the production of larger parts with higher aspect ratios, particularly for the consumer electronics market [120]. The main

focus of these developments has been to achieve a faultless surface finish and narrow part tolerances. This development is reflected in market interest in the production of smartphone frames [39]. The key to success in the case of parts with long flow paths and thin wall thicknesses is to perfectly coordinate the interaction between the mould, the

hot runner system and the dynamic mould temperature control system through the use of variothermal temperature control [10].

2C-PIM

For more than a decade, material hybrids encompassing two different material classes have increasingly emerged. Combinations of polymers and ceramics are reported by Becker [119], where the ceramic component has a key position for a certain application, as well as metal-ceramic material combinations [135, 136, 137]. The major advantage of 2C-PIM is the direct combination of two materials with different properties in a single production step, therefore eliminating the need for a subsequent joining process [48].

MicroPIM

MicroPIM continues to attract attention as a unique process by which to manufacture metal and ceramic micro components in medium to high volumes [77]. Injection moulding in particular is used for the production of both individual micro-components with typical dimensions of ≤ 1 mm and microstructured components, defined as micro- or even nanoscale structures on larger carrier surfaces.

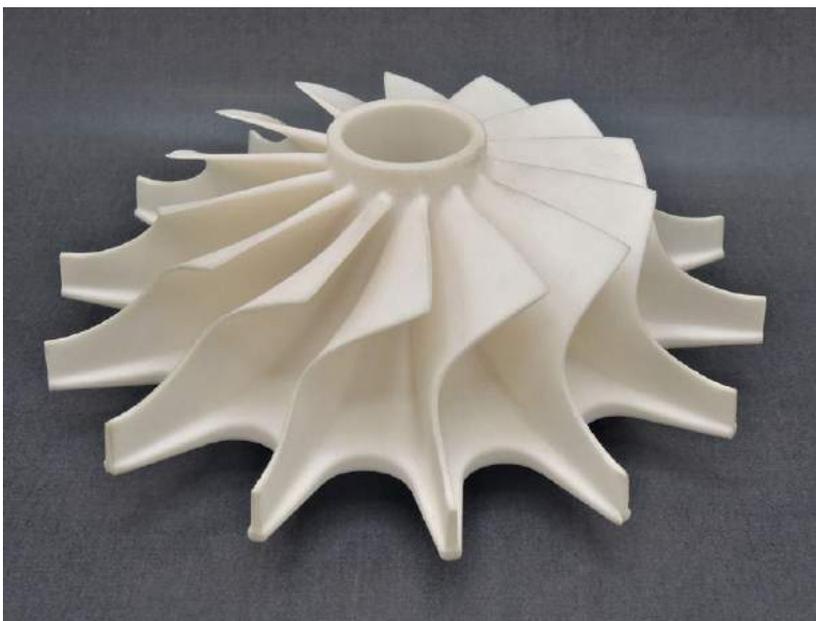


Fig. 24 Micro turbine impeller made of Si_3N_4 (diameter 103 mm) using CIM (Courtesy Fraunhofer IKTS)

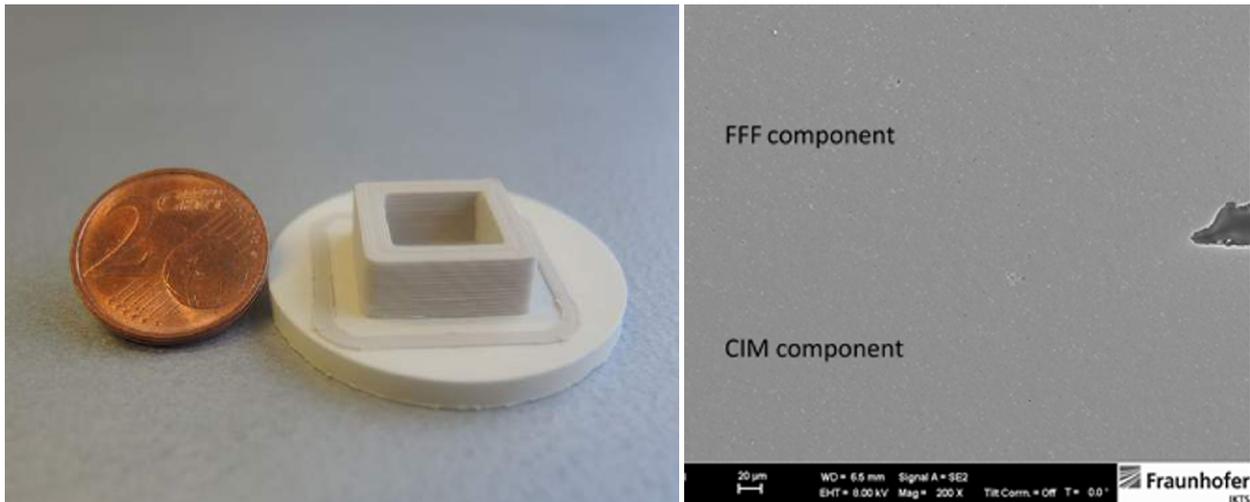


Fig. 25 Quadratic structure made by FFF applied to a cylindrical disc made by CIM (left: green state); FESEM image of the interface between both components (right: sintered state) (Courtesy Fraunhofer IKTS)

The trend towards further diversification in micro-manufacture, most notably a tendency towards using more varieties of functional or high-strength materials, takes advantage of the wide range of processable materials by MicroPIM. A further benefit can be obtained when two materials are combined in a micro device, enabling different functions to be realised. This can be enabled using 2C-MicroPIM [138].

The convergence of CIM and AM

Because of CIM's significant lead times and expensive tooling, it is very difficult to make cost-effective prototypes or small-scale series. Sometimes, however, it is necessary to have just a few parts in order to test an idea or for iterations to achieve an optimised design [139]. In such cases, ceramic AM can meet this need [140]. Additionally, the time for producing the mould could be reduced using AM. T Moritz *et al.* compared the pros and cons of AM and CIM [141].

It is very difficult to determine the break-even point between the two technologies, because there are two main drivers that play a crucial role: for CIM, it is the complexity of the part, which in turn determines the cost of the tool; for AM, it is the size of the part. These determine how many parts can be built in

parallel and how long it takes to finish one run. From the viewpoint of the composition of the initial materials, the two feedstock-based AM methods are Fused Filament Fabrication (FFF), which comes under the AM process category of Material Extrusion (MEX), and Multi Material Jetting (MMJ), a process in which droplets of molten feedstock are deposited to build up a green part. Both processes have much in common with CIM and can be regarded as close relatives of the technology [136].

A major advantage for CIM producers is that both processes can be easily implemented in existing PIM production settings using the same feedstock preparation machines. As such, they expand the potential range of products through, for example, the added capability for individualisation or personalisation. All powders that can be processed by CIM can also be used for FFF or MMJ. Furthermore, the same debinding equipment used in the CIM industry can also be used for AM components [136].

In the near future, a greater convergence between AM and CIM can be expected. For example, parts could be injection moulded by CIM, before undergoing an individualisation process using AM: a piece of ceramic jewellery could be created

with unique additively manufactured details. This flexibility could be taken so far as to enable the end customer to choose or design individual features, which are then applied to a piece of jewellery. This combination of ceramic shaping technologies could also lead to customised medical products covering a very wide range of applications, from dental parts to surgical tools [11].

Lost-Form PIM

As previously highlighted, Freeform Injection Moulding, also called Lost-Form PIM, combines the short lead times, low start-up costs and design freedom of Additive Manufacturing with the scalability and use of existing, lower-cost materials offered by injection moulding [54, 142]. It is based on a patent-pending Sacrificial Thermoplastic Injection Moulding (STIM) technology, which reportedly allows the production of complex injection moulded components in as little as twenty-four hours.

Digitalisation

The next technological boost in CIM will come from digitalisation. Applying artificial intelligence algorithms to enable machine learning will allow manufacturers to predict the quality of final sintered components after green part manufacturing. Ontology-based, pre-

trained models will be developed for the CIM community, which can be trained with the production data of each individual company. This will improve understanding of each product, help identify and correct non-optimal production parameters and enable the installation of robust processes. Product quality, resource efficiency and reliability will reach new levels.

The first steps have already been made: modern injection moulding machines are equipped with numerous sensors, which are the basis for assistance systems, as offered by Arburg [143]. However, since Powder Injection Moulding comprises far more than the moulding process, the initial powder and feedstock properties, thermal treatment and, if necessary, finishing steps must be covered in the process model as well. In order to profit from digital tools, an 'island' solution will not be enough. Rethinking and restructuring at CIM companies will be the challenge in coming years to achieve the breakthrough offered by Industry 4.0.

In summary, CIM parts development trends in the future will focus on:

- Very thin walls, combined with long flow distance
- Smaller or larger dimensions than usually considered for CIM parts
- Material hybridisation for multi-functionalisation
- The possibility to further leverage green machining
- Green part stability for mass production
- A robust process with less scrap due to advanced process modelling
- The efficient production of high volumes of CIM parts, multi-cavity or multiple moulds
- The individualisation of series components by closing ranks with AM technologies
- Small-series parts and prototypes via AM of lost-mould inserts.

Summary and outlook

Looking at CIM today, regarding the progress in material science, the development of Additive Manufacturing and the increasing influence of digitalisation on all spheres of life, it can be concluded that Ceramic Injection Moulding counts as a prospering advanced manufacturing technology for high-performance ceramic components. The spectrum of materials manufactured with CIM has been widened significantly, feedstock preparation has been qualitatively improved for more reliable and stable production cycles, tooling and machine equipment has been further developed for highly sophisticated ceramic products and the market situation for CIM looks very promising.

German focuses on three areas where growth in PIM is possible [7]. New materials are key: new applications should also align with longer-duration products, moving away from the fashion industry that takes up so much of PIM's capacity. The last growth opportunity is in improved processes: automation and closed-loop control will improve current practices and new technologies, such as fast sintering and Additive Manufacturing, offer obvious means to improve product quality.

Some of the most urgent industrial needs and challenges are paraphrased as follows:

- Improved dimensional control
- Improved process yield
- Reduced time to market
- Production of smaller lots
- Integrated continuous process improvement culture
- Improved skills [7]

The first two require more process control. This can be achieved by breaking away from a focus on individual steps and looking at the overall picture. Recognising interactions between process steps, material batches and product lines over an extended period will push the process knowledge. This demands the incorporation of integrated sensors,

closed-loop feedback control and analysis of gained data using process models. By mastering the process, developments become more predictable and the introduction cycles of new products can be shortened. Additionally, AM using the same powders and sintering cycles is a response to the third and fourth challenges. Finally, the last two challenges revert to personnel and training, sensor integration and embracing AM. In doing so, these challenges would be overcome [7].

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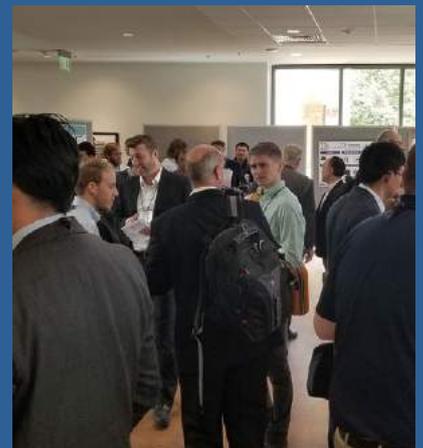
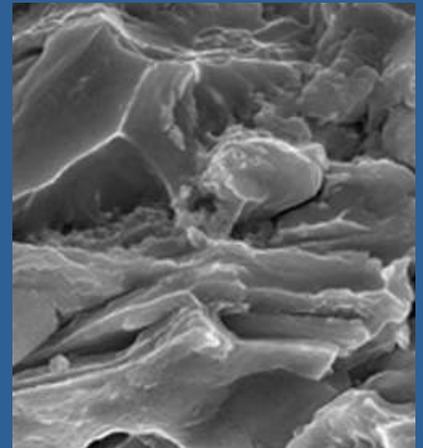
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ElementPlus: Exploring opportunities for titanium MIM in the consumer electronics sector

Asia's burgeoning consumer electronics sector has been the driving force behind much of Metal Injection Moulding's growth over the past decade. Can this sector now help drive the MIM of titanium? Leading Chinese Ti MIM specialist Shenzhen ElementPlus Material Technology Co., Ltd. believes that competitive powder prices, cost reductions thanks to more flexible processing, and the development of new applications with specific performance requirements, have created the perfect conditions for a breakthrough. The company's General Manager, Daomin Gu, shares her insights with *PIM International* and reports on progress to date.

Chinese Metal Injection Moulding producer Shenzhen ElementPlus Material Technology Co., Ltd. was established in Shenzhen in 2016. Today, the company's production facility is equipped with forty injection moulding machines, nine debinding furnaces and twenty sintering furnaces, and has the capacity to produce MIM parts worth 200 million RMB – around \$30 million – a year. Certified to international standards including ISO9001, ISO14000 and IATF16949, the company serves major OEMs from a wide range of sectors including consumer electronics, power tools and hardware, automotive and medical devices.

It is ElementPlus's research programmes, however, focused on MIM materials development, that have driven innovation and secured a strong market position for the company. Thanks to a well-resourced research laboratory operated by a group of specialist MIM engineers who work in close collaboration with universities and research institutes, technologies have been developed to enable the processing of a range of

different MIM materials. In addition to conventional iron-based alloys and stainless steels, ElementPlus's material portfolio includes soft magnetic materials, electronic packaging materials, tungsten alloys, lightweight alloys and ceramics. But it is the development of technology for the MIM of lower-cost, high-performance titanium alloy parts that is seen as presenting a significant opportunity for large-scale commercialisation.

Advantages of Ti MIM

Titanium and titanium alloys have attracted much attention from industry because of their high specific strength, good biocompatibility and excellent corrosion resistance. However, compared with other structural materials such as stainless steels and aluminium alloys, the high production costs of titanium alloys limit their applications to cutting-edge, high-tech and premium



Fig. 1 Inside the entrance of Shenzhen ElementPlus Material Technology Co., Ltd's modern MIM facility



Fig. 2 Views inside the ElementPlus MIM facility. Top; injection moulding area, middle; debinding facilities, bottom; vacuum sintering furnace installations

Challenges of titanium MIM

Titanium and its alloys are also challenging to process by Metal Injection Moulding. The major difficulty lies in the control of interstitial elements such as oxygen, carbon and nitrogen, all of which are detrimental to mechanical properties. Because the Metal Injection Moulding process consists of a series of stages including feedstock mixing, injection moulding, debinding and sintering – most of which are conducted at elevated temperatures – titanium powders, which have a larger surface area than bulk materials, easily pick up interstitials from the air, processing atmospheres, binder ingredients and ceramic setters.

Of the three main interstitial elements, the one of most concern is oxygen. Many research studies have indicated that even 3500 ppm oxygen can embrittle titanium alloys and make them unsuitable as a structural material. High-quality titanium powders available in the market contain over 1000 ppm oxygen. During sintering, the powder picks up a further 1500–2000 ppm oxygen and, once oxidised, the oxygen constituent in titanium cannot be reduced by any agents commonly used in industry.

Compared with oxygen, titanium picks up less nitrogen and carbon during sintering, though these two impurities are more harmful to the mechanical properties. Taking carbon, when its content exceeds 800 ppm, titanium carbide forms, reducing elongation, fatigue strength and corrosion resistance. Therefore, apart from carefully controlling the processing parameters of the injection moulding, debinding and sintering stages, choosing raw materials with low concentrations of interstitial elements is crucial to ensure that Ti MIM products have the required chemical compositions and necessary mechanical properties.

The powders used for Ti MIM are generally produced by gas or plasma atomisation, are spherical in morphology, and have particle sizes smaller than 45 µm. These types of powders are quite expensive,

application areas. Whilst the aviation sector is well recognised as the major consumer of titanium components, in the search for structural materials with better performance, the demand for titanium alloys from the electronics industry has also increased. Reducing the cost of titanium alloy components has, therefore, become an issue that must be urgently addressed in order to expand their use.

The high cost of titanium alloy components is partly attributed to the manufacturing processes by which they are made. Titanium is highly reactive in the molten state and

chemically reacts with almost all oxide refractory materials, meaning special melting processes are needed when casting it. Moreover, titanium has a low thermal conductivity, leading to ‘sticky’ tools and surface hardening when machined, which increases the cost of processing titanium alloys. Of the viable manufacturing processes for titanium alloys, MIM is one of the most suitable for producing structural components for the consumer electronics industry, which are typically small, complex, and must be produced in large volumes within a short period of time.

Specimens	Powder	Furnace hot zone	Density (%)	YS (MPa)	UTS (MPa)	Elongation (%)
CPTi	0–45 µm	metal	94.0 ± 0.2	432 ± 3	507 ± 5	14.5 ± 0.6
CPTi	0–45 µm	graphite	95.9 ± 0.1	445 ± 4	545 ± 7	15.4 ± 0.6
Ti6Al4V	0–25 µm	metal	99.5 ± 0.1	958 ± 11	1019 ± 12	21.5 ± 0.6
Ti6Al4V	0–25 µm	graphite	99.6 ± 0.2	1019 ± 3	1079 ± 2	22.5 ± 0.9
Ti6Al4V	0–40 µm	metal	96.8 ± 0.1	805 ± 1	918 ± 3	8.1 ± 0.6
Ti6Al4V	0–40 µm	graphite	97.2 ± 0.1	842 ± 10	958 ± 13	7.2 ± 0.4
Ti6Al4V	PolyMIM feedstock	graphite	96.5 ± 0.3	802 ± 1	915 ± 3	18.8 ± 0.4
Ti6.5Al2Zr1Mo1V	0–25 µm	graphite	96.4 ± 0.2	1038 ± 21	1093 ± 18	8.6 ± 0.8

Table 1 Summary of the mechanical properties of the MIM titanium and titanium alloys

thus making Ti MIM products less cost-competitive compared with MIM products made from other materials, as well as Ti products manufactured by other processes. There are many research projects aimed at producing Ti MIM products using lower-cost Ti hydride-dehydride (HDH) powders or TiH₂ powders, however these technologies have not yet been industrialised.

Apart from expensive raw materials, one factor pushing the price of Ti MIM products even higher is their sintering requirements. Unlike stainless steels, which can be readily sintered using more affordable and durable furnaces with graphite hot zones, Ti MIM products must be sintered in much more expensive furnaces with metallic hot zones. The heating elements and insulating materials of these furnaces are normally made from Mo or W, which gradually become brittle in service and need to be changed more frequently than their graphite counterparts, giving rise to higher maintenance costs.

It should also be noted that, in order to control oxygen concentration, the titanium powders used in MIM are coarser than stainless steels powders. This lowers sinterability compared with finer powders. Sintered densities in Ti MIM parts are therefore normally lower than in MIM stainless steels. The porosity in Ti MIM products not only compromises dynamic mechanical properties, but also excludes the possibility of achieving highly-polished surfaces, which are omnipresent in various consumer electronics.

Ti MIM materials research

Thanks to developments made in the metal Additive Manufacturing industry, a new generation of Chinese powder suppliers has invested significantly in establishing production lines for spherical titanium powder. Moreover, established titanium powder manufacturers are expanding their production capacity. The particle size distribution specifications of the standardised products of most manufacturers are: 15–45, 15–53, 45–106 and 45–150 µm, and powders with other particle size distributions can also be customised. Oxygen content is in the range of 800–1500 ppm and the most commonly used grades are pure titanium, Ti6Al4V and Ti6.5Al2Zr1Mo1V.

With coarser powders being consumed by AM and other Powder Metallurgy processes such as Hot Isostatic Pressing (HIP), the often-unwanted fine powders are the perfect raw materials for Metal Injection Moulding. As a result, powder suppliers can provide Ti powders at a far more competitive price. Thanks to this, Ti MIM products are gradually being accepted by China's huge consumer electronics industry.

Taking advantage of this, ElementPlus is undertaking further materials related research. In one study, three different Ti alloy powders (pure Ti, Ti6Al4V and Ti6.5Al2Zr1Mo1V) were used as raw materials. The powders were mixed with binders to produce a POM-

based feedstock that was prepared at temperatures below 185°C in order to reduce oxygen pickup.

In the subsequent injection moulding step, a low injection speed was used in order to reduce the friction of the powders, which can raise local temperatures in the feedstock and lead to decomposition and carbonisation of the POM binder. Catalytic debinding was conducted in a furnace at 100°C using nitric acid as the catalyser. Subsequently, the brown parts were transferred to another furnace for immediate thermal debinding and sintering, reducing contact with air to a minimum. After thermal debinding, the debound parts were sintered at temperatures ranging from 1200–1250°C, then cooled to room temperature inside the furnace.

In order to compare the influence of particle size on sintering behaviour, powders with three different size specifications (0–25 µm, 0–40 µm and 0–45 µm) were processed by ElementPlus. Two different furnaces, with graphite and metallic hot zones respectively, were used for sintering. In order to improve the level of the vacuum, a furnace with a graphite hot zone was modified in-house and used for Ti sintering. Samples sintered in this furnace were compared with those sintered in the metallic furnace to explore the possibility of manufacturing Ti MIM products with more affordable equipment.

Table 1 summarises the mechanical properties of the MIM titanium



Fig. 3 Two Ti6Al4V tensile specimens fabricated by Metal Injection Moulding, one in its as-sintered state and the other bent at a wide angle without fracture, indicating good ductility

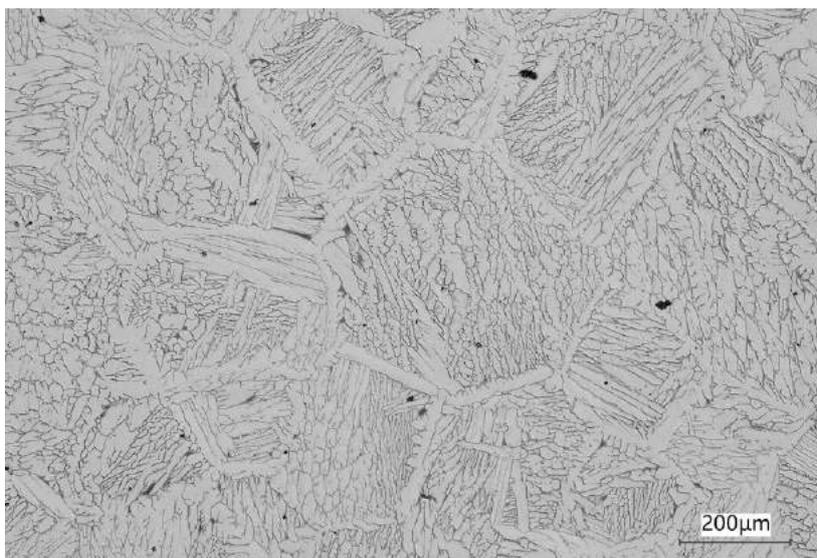


Fig. 4 The good mechanical properties of the Ti MIM alloy derive from its low interstitial concentrations and high sintered density, which is proven by an optical micrograph of the alloy showing an integrated microstructure with little porosity

and titanium alloys fabricated by the company. Ti6Al4V exhibits very good mechanical properties: it not only shows high strength in tensile testing, but also has elongation greater than 20% when well sintered. The ductility of the alloys is best illustrated by Fig. 3, which shows two Ti6Al4V tensile bars fabricated by MIM. One of these is shown in the

as-sintered state, while the other is bent at a wide angle. The bent sample does not fracture and shows no cracks on its surface despite the large plastic deformation. These positive mechanical properties derive from the low interstitial content, as well as the integrated microstructures of the alloy. Fig. 4 shows a micrograph of a Ti6Al4V sample fabricated by MIM.

With a sintered density of up to 99.5%, pores are rarely seen in the material’s classic two-phase microstructure. Compared with Ti6Al4V, the mechanical properties of pure Ti and Ti6.5Al2Zr1Mo1V are inferior. Due to their relatively low sintered densities, their ductility is not comparable with that of Ti6Al4V.

A comparison of the results for Ti6Al4V samples made from powders with different particle sizes indicates that the use of fine powder can effectively improve the sintered density and mechanical properties of the products, although the fine powders normally have higher oxygen concentration than the coarse ones. It is noted that samples sintered in different types of furnaces do not show much difference in sintered densities or mechanical properties. If carefully controlled, the graphite furnaces may sometimes even produce samples with ductility which is a little higher. This finding suggests that MIM companies might be able to save a large investment in expensive metallic hot zone furnaces, allowing mass-production of titanium alloys at a more competitive price.

Application potential

With the ongoing development of the consumer electronics industry, there are ever more requirements for light, structural materials with high strength. The high densities and good mechanical properties of the Ti MIM alloys developed by Element-Plus provide opportunities to cater to these requirements, which could not previously have been met by MIM. Some potential applications of the material are given below.

Watch cases

According to the latest data released by Counterpoint Research, global smartwatch sales reached 42 million in the first half of 2020. The growing smartwatch market therefore brings huge opportunities for the MIM industry, particularly for watch cases and buttons/crowns.

In addition to the required strength, hardness and corrosion resistance of these parts, the weight of the material used should be as low as possible, reducing the overall weight of the watch and improving wearer comfort. In addition to meeting the above requirements, titanium alloys also have excellent biocompatibility, eliminating the problem of allergic reaction posed by many currently-used Ni-containing watch case materials and making titanium an ideal material for wearable devices.

Previously, the utilisation of Ti alloys for high-volume watch case fabrication was prohibited by the price of the Ti MIM products and their relatively low sintered densities compared with other MIM materials. However, these problems have now been partially solved, paving the way for the large-scale commercialisation of Ti MIM parts in the fast-growing wearable device industry.

In collaboration with a well-known electronics industry leader, Element-Plus launched pilot-scale testing of smartwatch cases fabricated by the Metal Injection Moulding of Ti alloys. The results proved that most of the complex structural features of the watch case can be directly injection moulded within the required tolerance ranges, with only a few areas that have strict dimensional tolerances requiring CNC machining afterwards.

Thanks to a high sintered density of over 99%, most surface finishing methods, such as mirror polishing, surface brushing, sandblasting, PVD, etc, can be applied to sintered Ti watch cases to give a high-quality surface finish comparable with that of forged counterparts (Fig. 5 & 6).

Camera brackets for smartphones

Although Samsung first tried dual cameras as far back as 2007, it was not until 2016 that Huawei released its dual-camera smartphone, the P9, in cooperation with Leica. Apple then released the iPhone 7 Plus dual-camera smartphone in 2017. Since then, many other companies have developed their own multi-camera



Fig. 5 A Ti6Al4V MIM watch case which, thanks to a high sintered density over 99%, can be polished, brushed or blasted to achieve an attractive surface finish



Fig. 6 Ti6Al4V MIM watch cases with a variety of high-quality surface coatings



Fig. 7 Smartphone camera brackets made using P.A.N.A.C.E.A

smartphones, and there are ever more smartphones appearing on the market equipped with more than two cameras.

These developments pushed the demands on materials used for supporting brackets to new heights. Firstly, the material needs to be non-magnetic to avoid shielding the smartphone’s signal. Secondly, strength should be sufficiently high to protect the lens’s optical components. Finally, corrosion and wear resistance should be high enough to avoid the exposed part of the component being damaged or deteriorating during use. After much development, two alloys emerged: X15 CrMnMoN

17-11-3, widely known in its BASF Catamold form as P.A.N.A.C.E.A., and F75, a CoCrMo alloy. These have become the most popular materials currently being used for smartphone camera bracket fabrication (Fig. 7).

As the number of camera lenses continues to increase, the supporting brackets are becoming larger. The result is an urgent need to find a material which is as light as possible, whilst meeting the existing technical requirements for the brackets. Titanium has therefore become a potential candidate material for this application’s – and the wider smartphone industry’s – future.

Table 2 compares the mechanical properties of Ti6Al4V to those of the F75 and P.A.N.A.C.E.A. alloys, as well as other physical properties required and Fig. 8 shows the tensile curves. Ti6Al4V has a yield strength 50% higher than that of F75 and P.A.N.A.C.E.A. alloys; its hardness is also slightly higher than these. Additionally, Ti6Al4V has excellent corrosion resistance: in the salt spray test, the alloy can easily withstand the corrosion of salt solution for thousands of hours, making it orders of magnitude more durable than the F75 and P.A.N.A.C.E.A. alloys. Furthermore, Ti6Al4V is a paramagnetic material

Materials	Density (%)	YS (MPa)	UTS (MPa)	Elongation (%)	Hardness	Permeability	Salt spray test (h)
P.A.N.A.C.E.A	7.5-7.7	≥ 600	≥ 800	10-30	280-350 HV	< 1.04	~ 48
F75	7.9-8.2	≥ 550	≥ 800	8-15	300-330 HV	~ 1.01	~ 96
Ti6Al4V	4.3-4.4	≥ 900	≥ 1000	8-22	310-370 HV	~ 1.00	> 1000

Table 2 Comparison of mechanical properties of Ti6Al4V, P.A.N.A.C.E.A and F75 fabricated by MIM

with a permeability of only ~ 1.00004 . Its magnetic properties can easily meet the requirement for camera brackets (the acceptance threshold is set at 1.04 by most smartphone companies).

P.A.N.A.C.E.A.'s low permeability and high corrosion resistance derive from its nitrogen content, which is acquired during sintering and stabilises the austenitic structure of the alloy. However, the nitrogen content of P.A.N.A.C.E.A. is highly sensitive to processing parameters during sintering and heat treatment, making it one of the trickiest alloys for MIM processing. As a result, the properties of P.A.N.A.C.E.A. parts fabricated by MIM can show poor batch-to-batch consistency. On the other hand, low permeability and high corrosion resistance are intrinsic properties of Ti6Al4V and can be achieved consistently in its MIM products. From this aspect, it is expected that Ti6Al4V will result in a much higher yield rate in camera bracket production than P.A.N.A.C.E.A.

Hinges for foldable smartphones and smart glasses

In addition to camera frames, foldable screens are another milestone for smartphones. The core innovations lie in the combination of flexible screens and advanced hinges. The hinge of the foldable smartphone contains dozens of metal parts which are manufactured by MIM, CNC machining or stamping. The hinge material requires a yield strength greater than 900 MPa, good wear resistance, high hardness (greater than HRC 35) and light weight. Some parts have extremely high requirements in terms of dimensional and geometric tolerances, approaching the limits of the MIM process.

Currently, candidate materials for hinges include 17-4PH, 420, Fe-Ni low-alloy steel and Ti6Al4V. Titanium alloy parts have huge advantages in reducing the weight of phones: based on the same design, the weight of a hinge is around 60% of that of ferrous-based

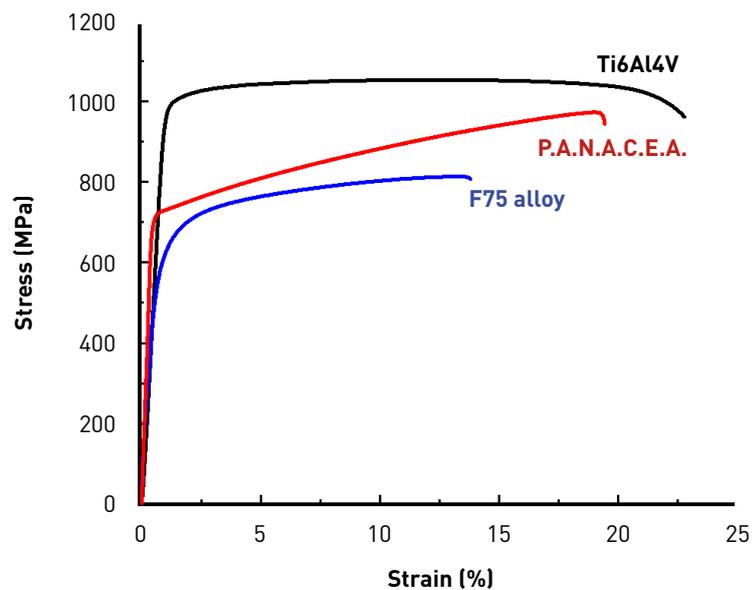


Fig. 8 A comparison of the tensile curves of three different MIM alloys, indicating that the yield strength of Ti6Al4V is much higher than the two alloys currently being used to produce camera frames of mobile phones – P.A.N.A.C.E.A and F75. This makes Ti MIM alloys potential materials for the future of smartphone bracket fabrication



Fig. 9 A pair of Huawei 'Gentle Monster' smart glasses with MIM Ti6Al4V hinges (Courtesy Huawei)



Fig. 10 MIM Ti6Al4V hinges for smart glasses

materials. With the development of foldable smartphones, MIM titanium alloy parts will therefore have significant potential market prospects.

Although MIM titanium is not yet used for the production of smartphone hinges, ElementPlus has mass-produced MIM Ti6Al4V hinges for several smart glasses, including the Huawei X Gentle Monster product. The hinge used here weighs just 0.25 g, which places a high requirement on the dynamic mechanical properties of the material (Fig. 9 and Fig. 10).

These components need to pass a fatigue test in which the components are bent back-and-forth by up to 7° deformation to simulate working conditions. Bending for at least 30,000 cycles without fracture is necessary to pass the fatigue test. This is a significant challenge, which requires strict control of the overall production process.

Conclusion

For many years, the view in the MIM industry has been that titanium MIM has failed to reach its market potential and start to rival other MIM materials in terms of significant production volumes. This has been, in part, due to a combination of challenging processing requirements, high powder costs, and a lack of applications. This picture may now be changing thanks to the timely combination of reduced powder costs, a greater mastering of the specific process requirements by a select number of MIM producers and, as highlighted in this article, some significant applications that bring with them the potential of high-volume production.

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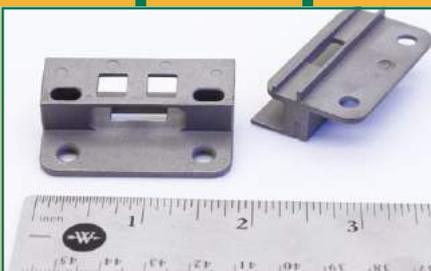
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MIM-Master Neo: A new generation of the continuous debinding and sintering solution that changed the MIM industry

When first introduced in the early 1990s, the MIM-Master continuous debinding and sintering furnace system from CREMER Thermoprozessanlagen GmbH, in combination with BASF SE's Catamold® feedstock, transformed MIM technology into a truly viable high-volume manufacturing process. Today, the system has been further enhanced, and the 'next-generation' MIM-Master Neo promises even higher capacity, improved temperature homogeneity and reduced running costs. In this article, the company's Jacqueline Gruber, Hartmut Weber and Ingo Cremer tell the story of MIM-Master and outline the innovations in the new system.

Metal Injection Moulding is a well-established and competitive manufacturing technology for the large- or small-scale production of small, high-precision and complex-shaped metal components, which are typically costly to produce by alternative processes. Whilst the technology is most widely used for metals, there are also process variants for the manufacturing of ceramics, intermetallic compounds and composites.

There are many factors to be considered when producing high-quality MIM parts. The quality and characteristics of each part are, however, dictated by their respective application. While in some cases an excellent surface finish can be the most important criterion, for example in consumer goods, in other applications, such as aerospace components, material composition – and thereby mechanical properties – will be the highest priority (Fig. 1).

To achieve high-quality products, manufacturers need reliable

thermal processing equipment with the capability to control and record the necessary thermal process parameters at any given time. The product range offered by CREMER Thermoprozessanlagen GmbH, a family-owned business based in Düren, Germany, includes a number of thermal processing

systems relevant to MIM. These include:

- MIM-Master: A state-of-the-art continuous debinding and sintering furnace
- Batch Sinter HDH: A batch furnace for sintering and the treatment of metal powders



Fig. 1 Examples of MIM components for distinct application areas: left, a Swatch Irony Sistem51 watch with MIM stainless steel case (Courtesy Swatch Group), and right, MIM IN713LC single-ended compressor stator vanes for the aerospace industry, shown after injection moulding (right), debinding (centre) and sintering (left) (Courtesy Schunk/Rolls-Royce)



Fig. 2 Thermal processing equipment for the MIM industry: top left, the MIM-Master system; top right, batch sinter HDH; bottom left, debinding unit TFE; bottom right, a compact Hot Isostatic Pressing (HIP) system (Photos © CREMER Thermoprozessanlagen GmbH)

processing solutions with a specific focus on extremely high production capacity, optimised temperature homogeneity and factory space utilisation, lower specific running costs and an improved system for the loading/unloading of sintering boxes.

The story of MIM-Master

Within the industry, MIM-Master is a well-established continuous debinding and sintering furnace solution that, today, has a leading position in the global market. Developed specifically for MIM, at its core is an advanced catalytic debinding system followed by a high-temperature walking beam sintering (WBS) furnace. The transport mechanisms throughout the system reliably deliver the extremely low levels of vibration that are necessary when moving very fragile parts through the plant – something that is of particular importance during the final debinding and sintering steps. Table 1 highlights the main application and characteristics of the MIM-Master system.

The MIM-Master system first gained momentum in the 1990s, a formative period for the global MIM industry. In 1992, CREMER Thermoprozessanlagen GmbH delivered the first continuous MIM debinding and sintering furnace system to Ecrimesa, based in Santander, Spain. The design of this first plant is very closely related to the system that would later become known as MIM-Master 3. Notably, the debinding zone was specifically constructed for catalytic debinding and was specifically tailored for parts manufactured using BASF SE's Cata-mold® feedstock system.

The '3' in the name MIM-Master 3 refers to the throughput capacity of the furnace, which is given in loaded sintering boxes per hour. In contrast to conventional 'press & sinter' Powder Metallurgy furnaces, where capacity is typically given in kg/h, this alternative classification was created to be particularly applicable to MIM furnaces, as in MIM the number of parts produced per hour is more relevant. The production capacity

Main characteristics of the MIM-Master system
High-capacity debinding and sintering
Debinding of POM or solvent-based feedstock systems
Sintering in N ₂ , H ₂ or argon for Fe-Ni alloys, stainless steels, duplex and tool steels, soft magnetic materials and heavy metals
Vibration free movement
High yield and efficiency

Table 1 Characteristics of the MIM-Master system

- Debinders TFE: A stand-alone debinding solution
- HIP: A compact Hot Isostatic Pressing solution tailored for the MIM industry

In addition, the company offers all the necessary services to ensure a high level of productivity, from the supply and installation of parts

to equipment maintenance and refurbishment — or the complete modernisation of existing industrial thermal processing facilities.

The company recently added a new MIM-focused thermal processing solution to its product portfolio. This new system, the MIM-Master Neo, represents the arrival of a new generation of MIM thermal



Fig. 3 A MIM-Master furnace (Photo © CREMER Thermoprozessanlagen GmbH)

in parts per hour can be easily calculated if the number of parts loaded on a layer, and the number of layers loaded on one sintering box, is known.

Several similar projects followed in Europe, notably the delivery of a MIM-Master 6 to produce high-quality consumer parts, such as Swatch's Irony watch cases. The MIM-Master system's design, which was based on well-established and proven industrial equipment solutions, represented a huge step forward for MIM production technology at the time. In fact, it set a new standard for MIM manufacturing plants, as it was the ideal solution for the sintering of 316L parts with a medium wall thickness, and average part weight of around 25 g. The MIM-Master 6 system was capable of processing approximately 110 tons of MIM feedstock a year.

In response to the need for increased production capacity, the MIM-Master 6 became one of the most popular debinding and sintering solutions in Europe at the time. The

MIM-Master 6 system, as its name suggests, has a throughput capacity of six sintering boxes per hour (Fig. 3).

At the end of the 1990s, the first MIM-Master 4 was delivered to China. This successful market entry in Asia was followed in the 2000s by further market expansion that saw several further systems delivered in Europe, North America and China. Encouraged by this, the company steadily continued to develop its technology, leading to the MIM-Master 8 system. This met the need for a further increase in production capacity, as well as greater demands for energy efficiency – something that was starting to become an increasingly important issue for all manufacturers worldwide.

The MIM-Master 8 featured the following innovations:

- A third-generation catalytic debinding unit with heating in the inside of the debinding channel
- An innovative ventilation system with the ability to generate axial 'lengthwise' gas flow, gener-

ated either as counterflow or crossflow

- Tight temperature control, thanks to temperature sensors placed close to the loaded parts
- Well-defined sintering times for all layers of the sintering boxes

Between 2010 and today, the maximum sintering temperature in MIM-Master furnaces has been increased steadily from 1,450 to 1,600°C. As a result, the system has become a viable option for the sintering of tungsten-based parts. In other applications, walking beam furnaces can reach up to 1,800°C.

The steady increase in MIM-Master throughput capacity and various models manufactured by the company CREMER over the years is shown in Table 2.

Thanks to its suitability for the large-scale production of MIM parts, the MIM-Master system is currently in operation worldwide to produce parts for a diverse range of applications in many industry sectors. It has even been re-engineered by

Furnace type	Sintering box type and dimensions (w × l × h)	Average capacity in terms of feedstock processed in t/a *
MIM-Master 4	Standard (230 × 330 × 90)	72.8
MIM-Master 6		109.2
MIM-Master 8		145.6
MIM-Master 10		182.0
MIM-Master 4XL	XL (330 × 330 × 90)	104.5
MIM-Master 6XL		156.7
MIM-Master 8XL		208.9
MIM-Master 10XL		261.1
MIM-Master 8XXL	XXL (420 × 420 × 120)	265.9
MIM-Master8XL Twin	2 lanes of XL (330 × 330 × 90)	417.8

* Estimated average capacity is determined by trays per hour (volume/h) for a 316L or 17-4PH cycle, 25 g/part, 300 days/24 h/day running three shifts.

Table 2 MIM-Master system capacities in tons/year

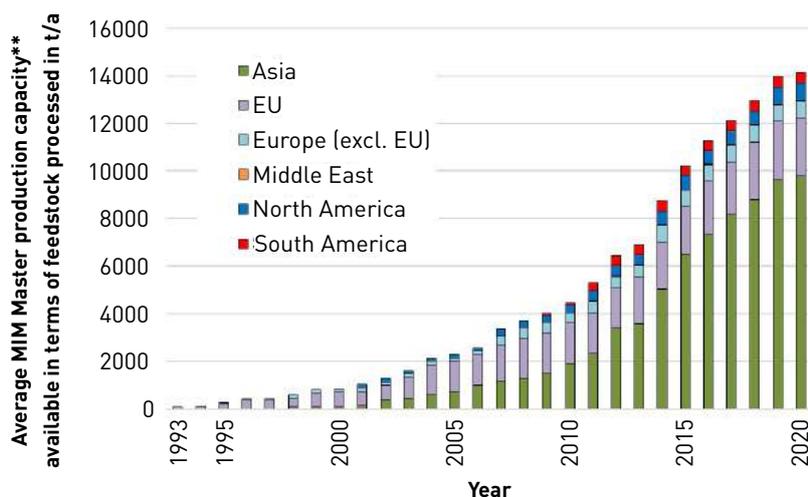


Fig. 4 Worldwide MIM production capacity available using existing MIM-Master installations ** Estimated capacity determined by trays per hour (Volume/h) for 316L or 17-4PH cycle, 25 g/part 300 days/a 24 h/day running three shifts

furnace suppliers in China – itself an acknowledgment that the system is regarded as the ‘gold standard’ in thermal processing equipment for the high-volume, continuous production of MIM parts.

Fig. 4 shows the contribution of MIM-Master systems to current overall MIM manufacturing capacity worldwide. This is based on the total number of installations and average estimated production capacity of each system sold since 1993.

The development of the MIM-Master Neo: the next generation of MIM-processing technology

Motivated in part by the ever-increasing pressure to optimise efficiency along the entire production chain, CREMER Thermoprozessanlagen GmbH has recently invested in extensive research and development to systematically develop a new

generation MIM-Master system, building on the industry-leading standards achieved so far. Developments had the following main aims:

- Optimised space usage
- Lower specific running costs
- Optimum temperature homogeneity of parts
- High production capacity
- An improved concept for loading/unloading of sintering boxes

In order to achieve the above, each individual element of the system and, most importantly, the specific process conditions within the debinding unit and heating zone of the walking beam sintering furnace were re-evaluated. For the debinding unit, gas flow, heating and process control were re-evaluated and adapted accordingly. The emphasis of development for the heating zone was placed on ensuring the best possible temperature homogeneity of the MIM parts during sintering, despite the high usable loading height in the furnace.

To overcome the difficulties that could be encountered during manual loading and unloading due to the increased weight of sintering boxes, a new solution to facilitate automation was designed. The corresponding sintering box concept is shown in Fig. 5 – in this instance limited to five levels, although up to eight levels have been achieved so far.

A new design for the heating zone was developed with the support of CFD simulations to investigate the heat and mass transfer within the furnace. The central section of the heating zone was studied, with the symmetry of the geometry and boundary conditions within this section of the continuous WBS furnace taken advantage of during modelling. A representative six loaded trays were used as the basis for the simulations.

Thermal radiation and conduction and the resulting natural convection within the heating zone were calculated using Ansys Fluent soft-

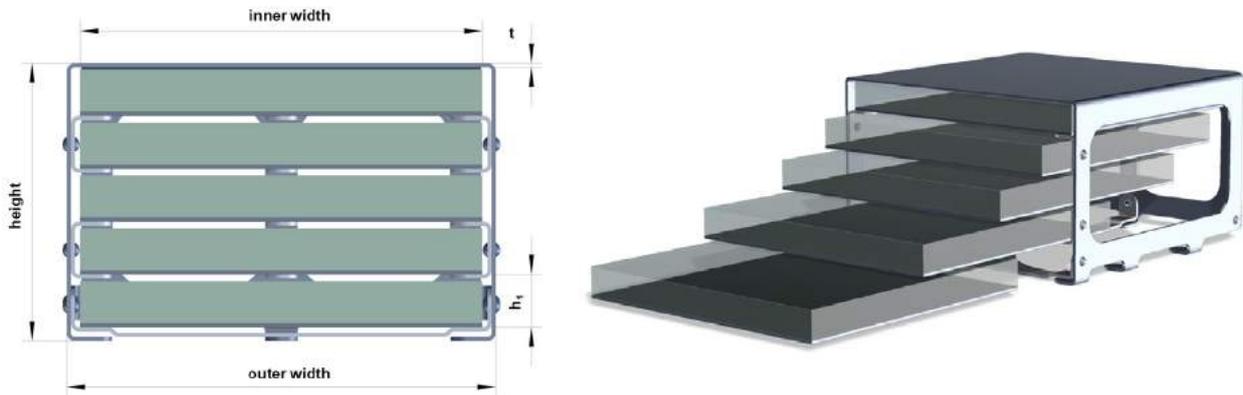


Fig. 5 New alternative concept for MIM-Master Neo sintering boxes for automation (Images © CREMER Thermoprozessanlagen GmbH)

ware. Several CFD simulations with different geometry configurations were carried out in order to analyse the changes in the interdependent gas flow and heat transfer conditions within the sintering zone. The simulated temperature distribution of loaded parts resulting from each design case was carefully evaluated and compared.

The main goal of the simulations was to optimise the system's operations in order to achieve the best possible temperature homogeneity in real-world operating conditions. The simulation results, which were necessarily obtained using a somewhat simplified model, had to, therefore, be interpreted in order to

understand the impact of complex flow field phenomena that will inevitably be present. Such phenomena, caused mainly by the transportation of the loaded trays through the WBS furnace, cannot be modelled using standard CFD methods.

Another challenge for such simulations is to define the boundary conditions appropriately. Several sets of boundary conditions were thus considered, including, amongst other things, the influence of gas flow along the central lengthwise axis of the furnace.

In addition to evaluating temperature homogeneity, the calculated temperature distributions within the furnace were used to reconsider the

insulation system of the furnace body. As a result, heat losses could be reduced, and higher energy efficiency achieved. Much was learned from the results concerning the influence on heat and mass transfer caused by specific changes in the geometry of the furnace interior – this was combined with observations and many years of field experience to obtain the best benefit from the theoretical investigations. An example of the simulation results for one case considered is shown in Fig. 6.

The result of the above developments is the new MIM-Master Neo. An international patent is pending for the new walking beam furnace

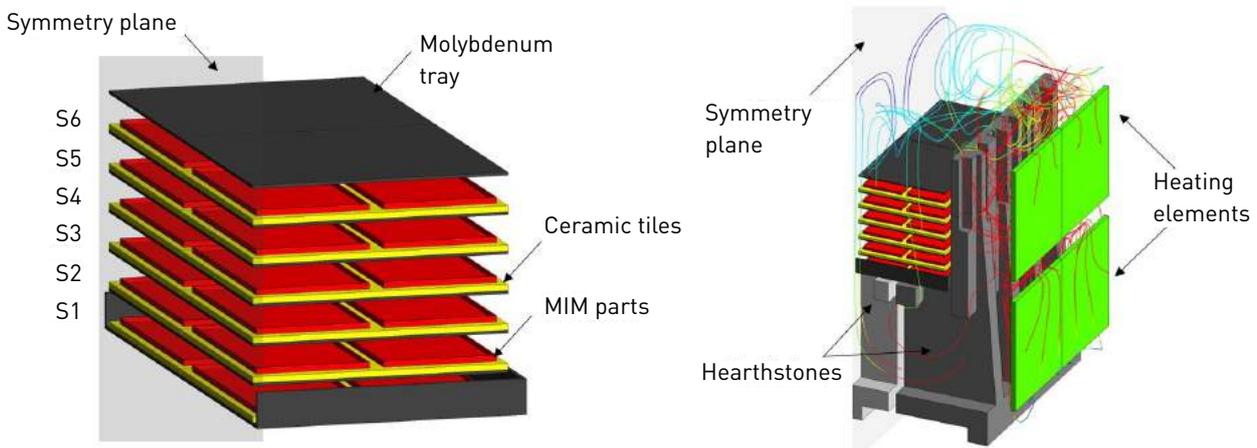


Fig. 6 CFD simulations used in the development of the MIM-Master Neo system (Images © CREMER Thermoprozessanlagen GmbH)

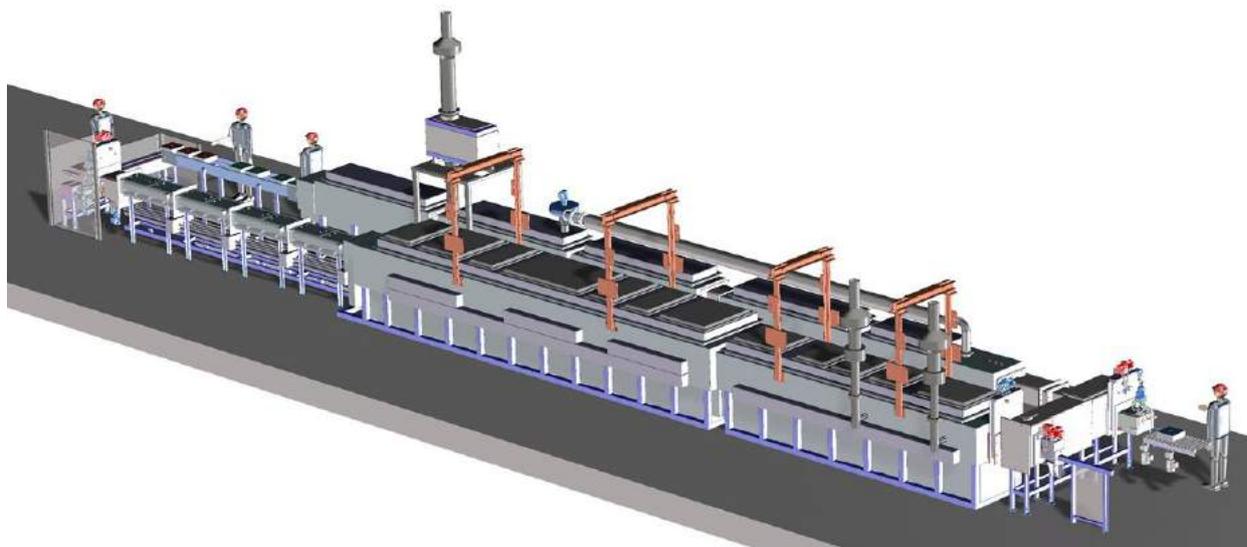


Fig. 7 Illustration of the new MIM-Master Neo (Images © CREMER Thermoprozessanlagen GmbH)

technology implemented in the new design [1]. Fig. 7 shows an example layout of the new system. As is the case for all MIM-Master systems, the layout can be customised according to a client’s requirements. Options range from the choice of sintering boxes to equipment, such as an additional zone for rapid cooling, or a unique layout for specific space requirements. The MIM-Master Neo’s innovations and advantages are highlighted in Table 3.

Conclusion and outlook

The Metal Injection Moulding industry has an important role in supplying innovative solutions to meet society’s needs as it adapts to increasing sustainability requirements. As an experienced developer and supplier of thermal process equipment, CREMER Thermoprozessanlagen GmbH is doing its part towards meeting these challenges by offering modern equipment that has been

optimised for the production of the parts needed for a range of new applications.

The new MIM-Master Neo is one example of this. Despite the past growth in production capacity, there is still a large potential for further growth as more MIM parts are integrated into new applications and technologies. The MIM-Master Neo system is therefore expected to replace the state-of-the-art continuous debinding and sintering technology currently on the market and help further increase the production capacity for high-quality MIM parts.

MIM-Master Neo features and innovations
High production capacity
Excellent temperature homogeneity of parts due to improved heating control
Higher energy efficiency thanks to the improved insulation of furnace body, leading to less heat loss
Optimised gas consumption thanks to efficiently-directed gas flow within debinding and sintering furnace segments
Optimised space utilisation
Reduction of specific consumption figures to approximately 75% of previous state-of-the-art values
Improved loading/unloading solution to take into account increased load weight due to the increased number of layers of each sintering box
Core elements of MIM-Master Neo plant can be supplemented by compatible additional CREMER equipment such as rapid cooling
Ultramodern Total Process Control (TPC4.0 HMI) with integrated furnace atmosphere control systems adapted to clients’ requirements

Table 3 Key innovations and features of the MIM-Master Neo system

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[1] Patent application WO 2020/125855 A1: Walking beam furnace and method for operating a walking beam furnace, published 25.06.2020

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Small-scale, complex parts with a fine surface finish: An AM solution from Incus meets the demands of MIM producers

There can be few Metal Injection Moulding companies who are not actively exploring the potential of metal Additive Manufacturing in their business. Whilst Binder Jetting and Material Extrusion-based processes are gaining much attention, particularly for the production of larger components, things become more complex when it comes to producing the parts that fall at the smaller end of MIM's size range, where surface resolution and finish become even more critical. In this article, Dr Gerald Mitteramskogler shares insight into Incus GmbH's Lithography-based Metal Manufacturing process with *PIM International* and explains why it is so well suited to use by MIM producers.

Driving innovation at manufacturing companies requires them to embrace new technologies and ways of working to meet growing demands of end-users industries. In the Metal Injection Moulding industry, forecasts for the coming years predict a continuous high demand for complex parts and a need for shorter response times to get a functional prototype to the customer. In many cases, for example in medical applications, these requests require small batches of parts (< 5,000 pieces per year) for initial studies. This is challenging for many MIM producers, who must often decline these requests due to the high setup costs for the mould and configuration of smaller-scale production, as well as additional resources and time developing iterations of the initial prototype.

While MIM is a process suitable for medium- and large-scale production, it lacks the ability to achieve quick turnarounds and is unable to match the required efficiency levels for manufacturing at a small lot scale or on-demand.

Incus GmbH, an engineering company based in Vienna, Austria, is working to help bridge the gap in this process for the MIM industry with its metal Additive Manufacturing (AM) technology, with AM acting as the 'missing link' for MIM producers in the development and production scale-up process.

AM technologies can be applied to produce initial functional prototypes; manage the development process efficiently through design iterations; and even as a more economical solution for a small-scale production. It is important to note, however, that for metal AM to be a true asset to MIM, the technology must be able to



Fig. 1 Cufflink prototypes manufactured using Incus's metal AM technology. The surface finish and level of detail achievable makes the technology complementary to the MIM process



Fig. 2 The Hammer Lab35 metal AM system from Incus is based on Vat Photopolymerisation (VPP) technology, also known as lithography. As with MIM, the green parts produced required debinding and sintering

produce parts that are comparable to those made by MIM in terms of surface aesthetics, dimensional accuracy and mechanical properties. Only if these three factors are combined can effective functional prototypes or small-scale part production be offered to the customer.

MIM end-users are typically not concerned about whether a part is produced by MIM or by a 'MIM-like' AM process, but are more focused on the quality of the part, whether it meets the needs of the final application, and that it can be produced in a cost- and time-effective manner.

Incus has developed a metal AM solution based on Vat Photopolymerisation (VPP) technology, also known as lithography. The system, called Hammer Lab35 (Fig. 2), is

designed to deliver this combination of part functionality and production economics to the MIM industry.

"As an AM technology provider, we need to focus on the fact that the customers using our technology need to make money using the machines, materials and services," stated Dr Gerald Mitteramskogler, founder and CEO of Incus GmbH. "The MIM producers and end-users we work with find the AM approach interesting; however, in the end, they typically do not care how the part was manufactured as long as their needs are met in the most efficient way. We aim to provide our MIM customers with the ideal bridge for cost- and resource-effective development of parts, scale-up and smaller-scale production for their customers."

Incus – an up and coming company in the AM hub of Vienna

In 2015, during the European research project ReProMag, a new AM approach was successfully developed by Mitteramskogler at Lithoz GmbH, a leader in the Additive Manufacturing of technical ceramics. Although the goal of processing magnetic powder using Lithoz technology proved to be challenging due to the reactive nature of the material, a new lithography-based approach was developed with the ambition of transferring Lithoz's success with ceramics to the processing of metal powders.

After four years of development and three prototypes, in September 2019 the progress of the technology convinced Lithoz and specialist investment house AM Ventures Holding GmbH to found a separate company focused only on metals. Since then, Incus has been working with key partners and customers to roll out and further develop its lithography-based metal AM technology with a focus on the MIM industry.

A new interpretation of metal AM with lithography

Incus's Lithography-based Metal Manufacturing (LMM) process works on the principle of photopolymerisation, where metal powder is homogeneously dispersed in a light-sensitive resin and selectively polymerised by exposure to light. This mixture is then applied layer by layer with a coating blade during the build process. The light projection unit then cures each layer as it is deposited, providing a resolution of 2560 x 1600 pixels, with a pixel size of 35 µm, to achieve outstanding surface aesthetics and build fine geometries.

The Incus Hammer Lab35 has a build platform size of 89.6 mm x 56 mm x 120 mm (L x W x H). Besides the size of the platform, and therefore part volume, there are no other restrictions concerning the part.

With this LMM process, it is possible to use MIM-grade metal powders down to 8 µm (average particle size) at competitive build speed to other indirect or two-stage AM approaches, such as Binder Jetting.

The feedstock is a proprietary blend of photo-reactive resins, waxes, additives and metal powders with a solids loading of up to 55 vol.%. This composition allows for a wide range of metals to be processed, from 316L stainless steel to titanium, copper, tungsten, precious metals, carbides and many more. Incus also offers innovation studies to work on new materials and applications with customers and to provide a starting point with the LMM technology. It only takes roughly ten minutes to get from a metal powder to a clean block of feedstock ready for Additive Manufacturing or process evaluation. Whilst many metal AM technologies have a reuse rate of < 50% of leftover powder, the Incus LMM process enables 100% waste feedstock reuse, enhancing resource efficiency and sustainability in the manufacturing cycle.

Unlike many metal powder AM systems, lithography-based AM operates at room temperature. The heated blade melts and evenly spreads the feedstock over the build platform. After coating, the machine cools down the layer and the feedstock turns solid, similar to the melting and hardening of candle wax. The liquid nature of the feedstock during the coating step helps to avoid streaks or other imperfections in the coated layer.

Since a new layer of material is always coated on a solidified layer, the interaction of the already-created layer and the newly-coated layer is minimal. The layer thickness depends on the metal powder used and typically ranges from 10 to 100 µm. The build speed is determined by the thickness of the layer rather than the part volume, since the layers are polymerised with a projector unit and therefore the whole layer is projected at once. For example, with a layer thickness of 25 µm the build speed would

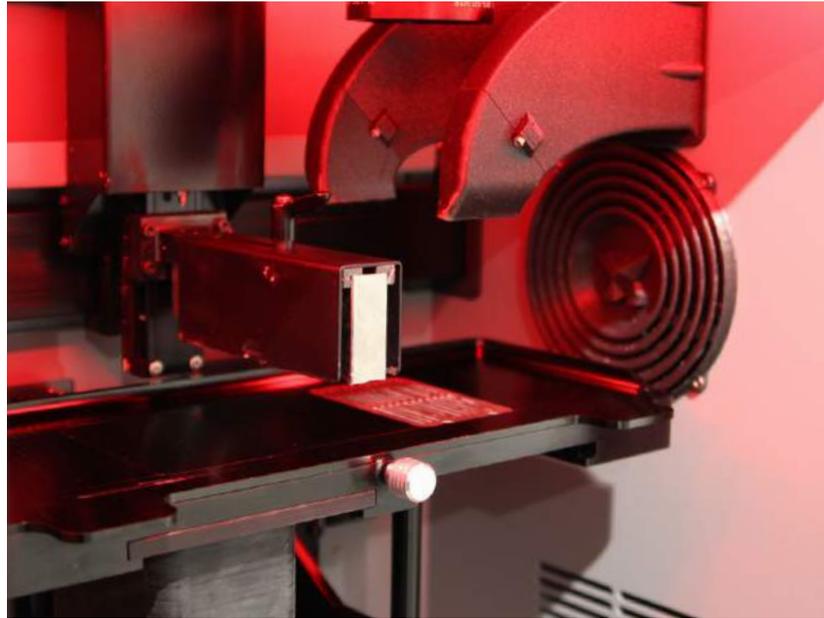


Fig. 3 A view inside of the Hammer Lab35 build chamber

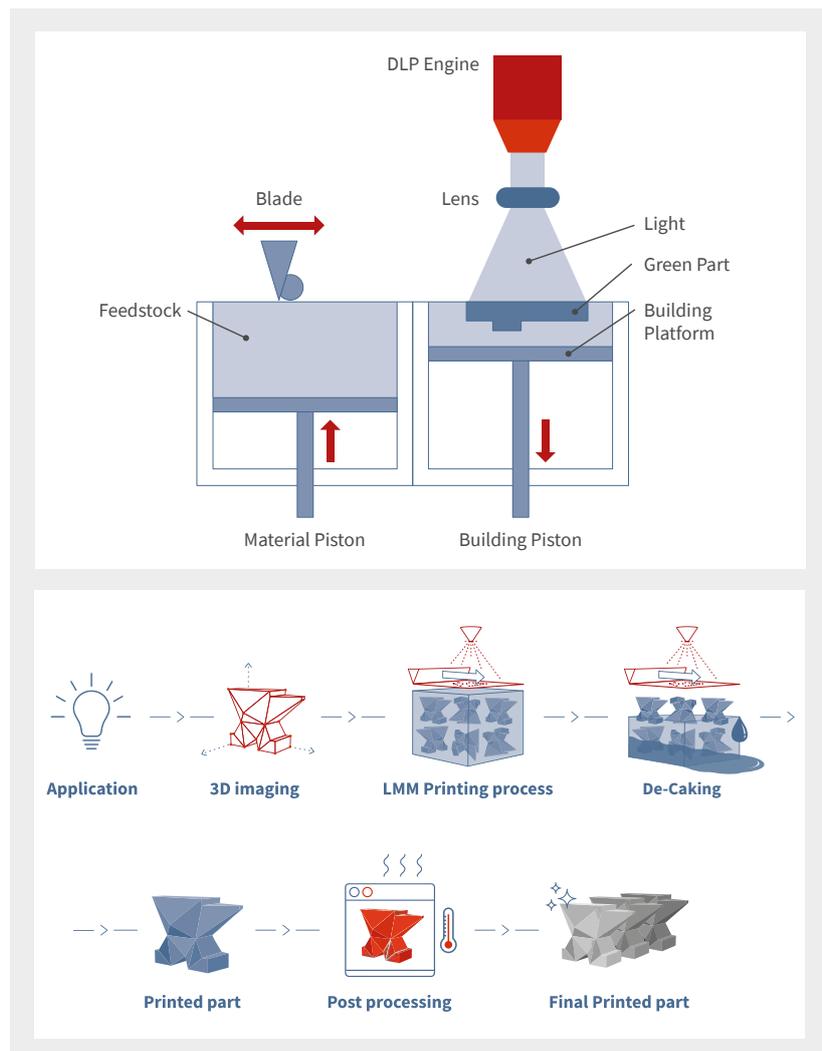


Fig. 4 Top: schematic of the build process in the Hammer Lab35 machine; bottom: the process flow from concept to final part



Fig. 5 A selection of parts manufactured by Incus using the Hammer Lab35 machine

be 10 mm/h and the whole build volume can be completed in less than twelve hours. The build speed increases as the layer thickness increases, but the trade-off is a decrease in resolution in the build direction.

A flexible process with MIM-like surface quality and thermal processing steps

Once all of the layers are built, the result is the green part – a combination of metal powder held together by a binder – which is enclosed in the block of feedstock material. This surrounding feedstock allows parts to be built without additional support structures. After this building step, a simplified post-processing requires only fifteen minutes to ‘de-cake’ the block, releasing the green parts. Since no loose powder is involved, this melting process is safe and clean for the operator.

“The combination of the high-quality coating mechanism and the industrial projector unit provides MIM-comparable part aesthetics and resolution, especially for smaller parts.”

The combination of the high-quality coating mechanism and the industrial projector unit provides MIM-comparable part aesthetics and resolution, especially for smaller parts. This advantage differentiates LMM from other existing AM technologies. Because of the photopolymer chemistry, the green part strength is sufficient to allow the manual handling of smaller structures.

“For the first time in metal AM, Incus offer a unique process that combines excellent feature resolution, surface aesthetics and

mechanical properties with an economic process for part sizes < 200 g,” explained Mitteramskogler.

The final post-processing steps, debinding and sintering, allow the green parts to achieve mechanical properties equivalent to a metal part made by MIM. As with metal injection moulded parts, lithography-based metal manufactured parts undergo 16–20% shrinkage during sintering, which is already taken into account in the product design.

“The manufacturing of the green parts is just one step in the whole production chain. We are able

to print the most sophisticated green parts — however, if design guidelines, which are similar to MIM, are not carefully followed and understood by the part designer, parts might show distortion due to gravity, or will not shrink homogeneously,” stated Mitteramskogler. “Because this is an interesting challenge, we enjoy working with the MIM producers. Here the necessary expertise is already available and the engineers are aware what’s possible in the design and what’s not.”

In MIM, the tooling factor or sinter compensation is a very important factor carefully tailored to a specific feedstock and part design. If the tooling factor of a mould needs to be adjusted, a lot of effort needs to be put into the reworking of the mould. Since LMM can be considered ‘freeform’ in comparison to MIM, the correct tooling factor can be established with simple and quick design iterations and the same part can be built to different scales on the building platform. After sintering, the most fitting tooling factor of the part can be chosen.

With LMM, no build support is needed for overhangs or to connect the parts to the building platform. Similar constraints apply as for MIM when it comes to sintering; however, when sintering supports are needed, these can be manufactured with or separately to the part or, if larger part quantities are required, ceramic setter plates may be a more economic solution.

The surface roughness of the sintered parts largely depends on the particle size of the powder used and is typically $< 5 \mu\text{m Ra}$ in every direction without any additional surface treatment. Sintered parts made of 316L stainless steel can reach a density of 98.2–99%, based on a theoretical density of 7.87 g/cm^3 . By making slight adjustments to a standard MIM debinding cycle, the carbon content of sintered cubes with a dimension of 10 mm^3 was able to be optimised and a carbon value of 0.03 wt.%



Fig. 6 Drill heads components



Fig. 7 Many dental applications are ideally suited to metal AM thanks to the ability to offer previously impossible levels of customisation

was measured. Besides the carbon content, all other elements were as specified by the ASTM Standard E8.

“As we have developed this LMM technology, it has been further proven that it is complementary to MIM mass production, especially due to its effectiveness in producing speciality parts with fine geometries,” commented Mitteramskogler. “Our technology

enriches the MIM process with design freedom and speeds up the product development while substantially reducing lead time. Using metal AM as a quick first step helps manufacturers jump start development by offering their customers additional options before the full-scale production. This allows them to ensure they are producing the best parts for their end users from the start, before scaling up.”



Fig. 8 An electronics cooling device developed by Incus, measuring 33 x 27 x 7 mm

Medical devices to luxury goods: LMM's applications

Metal Additive Manufacturing, and specifically Incus's LMM technology, can be applied in a wide range of industries and applications for parts ranging from drill heads and conformally-cooled mould inserts, to fine luxury jewellery, tiny dental brackets and hinges for glasses.

Moulds and tools

Shorter time-to-market, wide range of previously impossible design options and lower production costs have driven the injection moulding industry to adopt Additive Manufacturing for the fabrication of tooling for injection moulding. The wider manufacturing sector is also a major consumer of LMM parts for applications that include sensor housings, nozzles, turbine wheels and drill heads (Fig. 6). The parts are typically made from 316L stainless steel and demonstrate the high-quality finished parts that can be achieved with the technology.

Medical and dental

It is well known that many medical parts for surgical devices and laboratory equipment are niche products with complex geometries and fine features, produced in small series. One of the first major application areas of LMM was dentistry, the production of dental brackets, crowns, bridges, implants and surgical grippers made from 316L stainless steel or titanium alloy Ti6Al4V (Fig. 7).

Consumer goods

LMM has already established itself as a cost-efficient means to produce complex parts needed in small batches for watches, eyewear, jewellery, and luxury goods industries more generally where quality and surface aesthetics are crucial. Using additively manufactured design prototypes, rather than creating test moulds, reduces manufacturing costs significantly and allows freedom in development and

optimisation before bringing the final design to the market.

Electronics

The demand for smaller, high-precision components with optimal performance and lower cost has allowed LMM technology to thrive in the electronics industry, producing high-strength mobile phone cases, SIM-card holders or cooling devices (Fig. 8). In these applications especially, LMM shows its strengths with exceptional accuracy and ability to produce highly-complex parts.

The future is bright for metal AM

Although AM is well known in the MIM industry, there is still ample room to realise all of the benefits the technology has to offer. Since the MIM industry is designed for mass production, integrating AM-based small-scale production into the workflow requires a

different mindset. Lower quantities of specialised components might offer a business model with higher margins. Conversely, being able to offer functional prototypes prior to MIM mass production could help to establish a closer customer relationship and speed up the design iteration process. AM could also enable spare part production after a product's lifecycle has come to an end, which is something the MIM industry has not yet been able to integrate into its workflow. However, since the concept of weaving AM into the MIM workflow is still relatively new, the monetary benefits of the integration are difficult to evaluate at this stage.

"The benefits AM can provide to MIM manufacturers are clear, but it will take a few key producers to take a leap of faith and join us in establishing this new interface and best-practice processes," concluded Mitteramskogler.

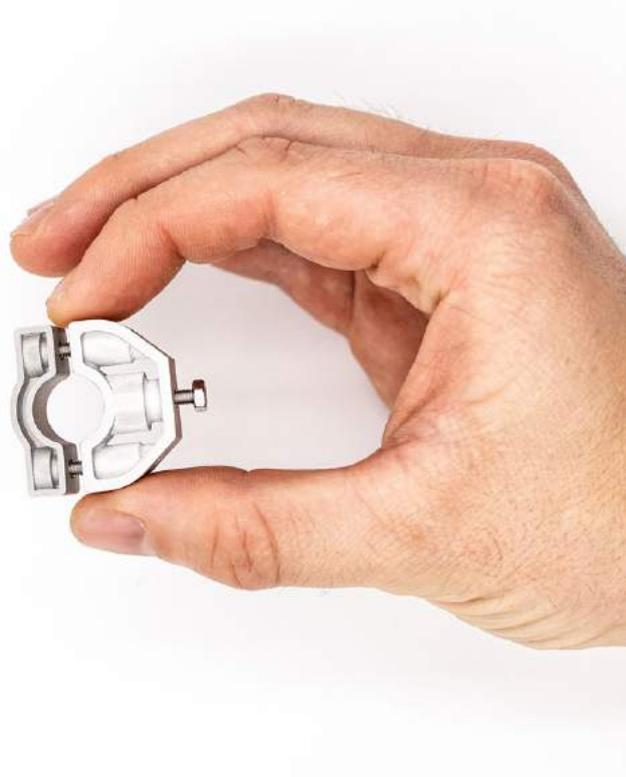


Fig. 9 A stainless steel sensor holder manufactured by Incus

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