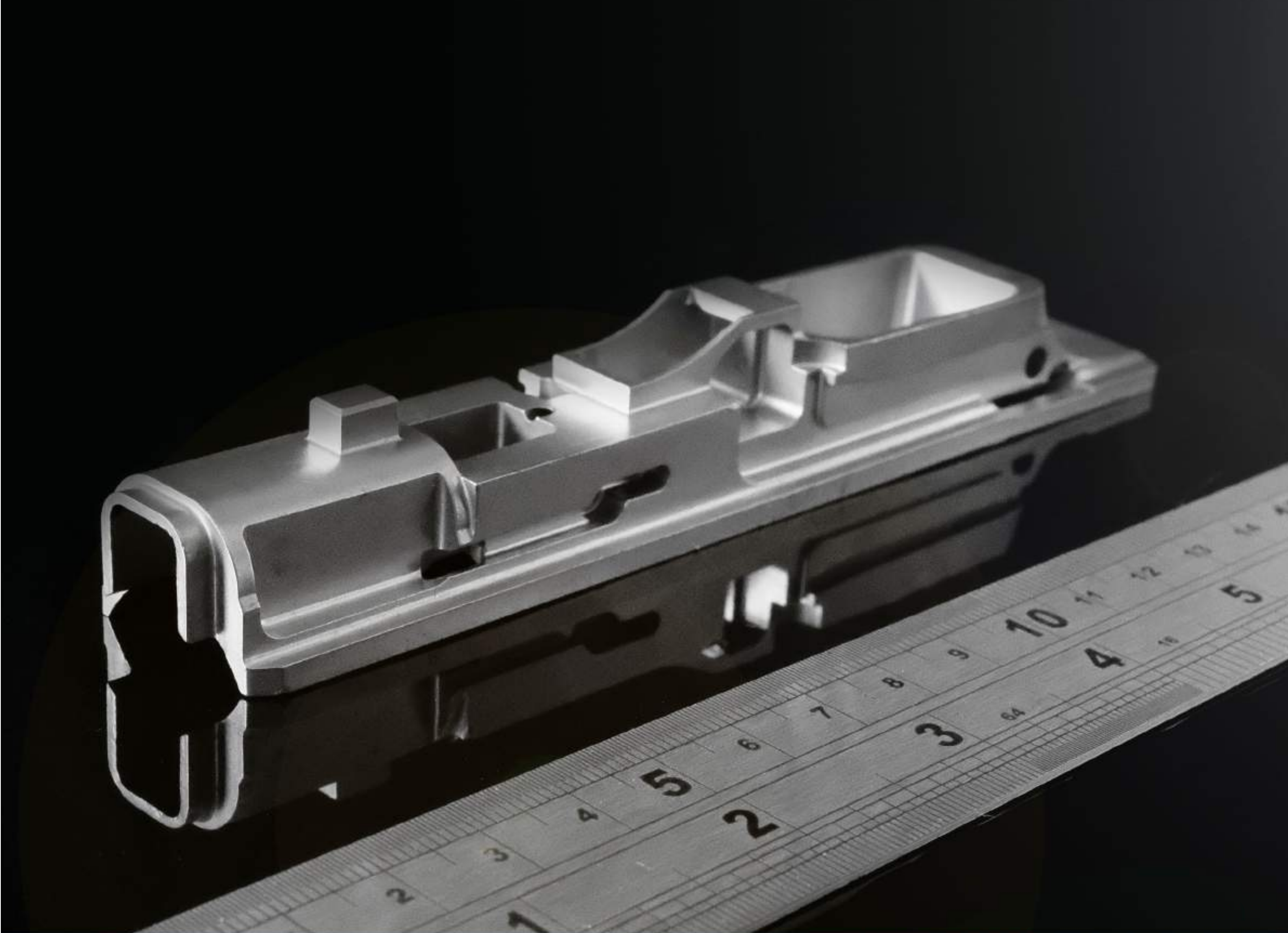
Vol. 13 No. 4 DECEMBER 2019

FOR THE MIM, CIM AND SINTER-BASED AM INDUSTRIES

POWDER INJECTION MOULDING INTERNATIONAL



Mimecrisa: pushing MIM's limits

PMTi2019 conference review

MIM of Nimonic 90

Published by Inovar Communications Ltd

www.pim-international.com

Publisher & Editorial Offices
Inovar Communications Ltd
11 Park Plaza
Battlefield Enterprise Park
Shrewsbury SY1 3AF
United Kingdom
Tel: +44 (0)1743 211991
Fax: +44 (0)1743 469909
www.metal-am.com

Managing Director & Editor
Nick Williams
nick@inovar-communications.com

Publishing Director
Paul Whittaker
paul@inovar-communications.com

Deputy Editor
Emily-Jo Hopson
emily-jo@inovar-communications.com

Assistant Editor
Kim Hayes
kim@inovar-communications.com

Consulting Editors
Prof Randall M German
Former Professor of Mechanical Engineering, San Diego State University, USA
Dr Yoshiyuki Kato
Kato Professional Engineer Office, Yokohama, Japan
Professor Dr Frank Petzoldt
Deputy Director, Fraunhofer IFAM, Bremen, Germany
Dr David Whittaker
DWA Consulting, Wolverhampton, UK
Bernard Williams
Consultant, Shrewsbury, UK

Production Manager
Hugo Ribeiro
hugo@inovar-communications.com

Advertising
Jon Craxford, Advertising Sales Director
Tel: +44 (0)207 1939 749
Fax: +44 (0)1743 469909
jon@inovar-communications.com

Subscriptions
Powder Injection Moulding International is published on a quarterly basis as either a free digital publication or via a paid print subscription. The annual print subscription charge for four issues is £145.00 including shipping.

Printed by
Cambrian Printers, Aberystwyth, United Kingdom

ISSN 1753-1497 (print)
ISSN 2055-6667 (online)

Vol. 13. No. 4 December 2019

INOVAR COMMUNICATIONS

POWDER INJECTION MOULDING INTERNATIONAL

For the MIM, CIM and sinter-based AM industries

Misunderstood, full of potential and more capable than people think

If technologies could be graded by human life stages, then judging by the feedback from the recent Powder Injection Moulding showcase at Formnext 2019, PIM might easily be mistaken for a stereotypical teenager – the extent to which the technology is misunderstood was a real surprise. Thankfully, our display of more than a hundred impressive, real-world MIM and CIM applications provided ample proof that the technology is far more capable than people first think and served to effectively dispel many misconceptions.

For visitors who were totally unaware of PIM prior to their visit, the technology was a revelation. The gleaming parts, in brightly-lit showcase cabinets, acted as a magnet to passers-by who were – given that Formnext is primarily an Additive Manufacturing show – inevitably looking for parts from very different and far less mature technologies. When after much curiosity they realised that the parts were not AM but made by a net-shape, high-volume process that was totally new to them, the enthusiasm was palpable.

The questions asked by visitors to the showcase are all too familiar to those in the industry: How could such complex shapes be moulded? How are such high densities achieved? And how can the parts really shrink to a predictable shape during processing? It was, however, some of the more complex components that really aroused curiosity, including parts with internal channels created using dissolvable cores and 2C/two material PIM components.

And so the task of promoting PIM technology goes on. From collaborations such as the successful PIM showcase at Formnext to the daily activities of PM trade associations and individual companies, progress is being made – even if it feels like just the tip of the iceberg.

Nick Williams,
Managing Director & Editor

Cover image
This firearms component is at the largest end of MIM's size range (Courtesy Mimecrisa)

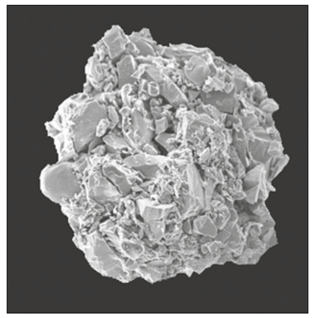
December 2019

Powder Injection Moulding International

13

15

57



73

79

In this issue

Regular features

Industry News

MIM2020: Technical programme published for international PIM conference

The MIM2020 International Conference on Injection Molding of Metals, Ceramics and Carbides, will be held at the Hotel Irvine, in Irvine, California, USA, from March 2–4, 2020. This global conference and tabletop exhibition highlights advances in the Metal Injection Moulding industry and is the only international MIM conference of the year.

The event will once again be preceded by Randall M German's popular annual Powder Injection Molding Tutorial, which he has been leading since it was first presented in 1990. The optional course (which requires a separate registration fee) is an ideal introduction to PIM technology, offering a comprehensive foundational understanding within one day. The topics covered are:

- An introduction to PIM manufacturing, from feedstocks to moulding, debinding, sintering and finishing
- The definition of what constitutes a viable PIM component
- The selection of materials based on component expectations and required properties
- The assessment of the critical features of dimensional accuracy and material performance
- A comparison of PIM and competing technologies
- A review of the economical advantages of PIM
- A look at new applications, emerging markets and examples of products thought impossible to manufacture to net shape until PIM

German will also open the conference sessions with his keynote address, 'The question: is MIM there yet?' This presentation will look at some of the historical key points in MIM's development, as well offering an assessment of the current status of the industry.

Both conference sessions will feature a range of technical presentations from the industry and academia, interspersed with the presentation of design case studies and technology process and product innovations.

Reflecting the growing overlap between MIM and sinter-based metal Additive Manufacturing (AM), some presentations will cover topics common to both fields, such as how metal Binder Jetting can meet MIM standards.

A tabletop exhibition will see international MIM suppliers showcase their products and technologies. There will also be a networking reception open to all attendees of the conference, with beverages sponsored by *PIM International*.

The full technical programme and further information on MIM2020 are available via the MPIF website. The deadline for discounted early-bird registration is January 17, 2020.

www.mpif.org/events/mim2020

UK-based MIM manufacturer showcases razor head manufacturing

CMG Technologies Ltd, a manufacturer of precision components by Metal Injection Moulding based in Rendlesham, Suffolk, UK, recently showcased its process for producing razor heads by MIM in a television documentary focusing on British manufacturing, titled 'Made in Britain'. The company produces MIM razor heads for Edwin Jagger Safety Razors.

CMG Technologies is the only business in the UK to offer commercial MIM services. The company has been providing MIM for more than twenty years, which includes supplying a reported 40,000 MIM scalpel handles a month to the UK's National Health Service.

Rachel Garrett, Director at CMG Technologies, commented, "We have worked with Edwin Jagger Safety Razors for two years, providing them with top and bottom plates for their crafted safety razors, and to be able to show the part that we play in producing a British-made product is fantastic."

"Not many people know about the process of Metal Injection Moulding and how effective it is in producing intricate parts with little waste, so the documentary is great exposure for a somewhat little-known process," Garrett added.

www.cmgtechnologies.co.uk

Edwin Jagger 3ONE6 stainless steel knurled safety razor head, produced by Metal Injection Moulding (Courtesy Edwin Jagger Ltd)

ExOne announces X1 160PRO Binder Jetting system for high-volume production

The ExOne Company, North Huntingdon, Pennsylvania, USA, has announced its newest machine and largest metal Additive Manufacturing system to date, the X1 160PRO. Designed for high-throughput and large-part production, the new X1 160PRO will reportedly offer build dimensions of 800 x 500 x 400 mm and build speeds of up to 10,000 cm³/hour.

"Our technology roadmap has been leading us to this machine for more than two decades," stated John Hartner, ExOne CEO. "At the same time, the X1 160PRO was also designed in response to growing demand from automotive, defence and aerospace customers. We're incredibly proud of what this model means for the future of metal 3D printing and sustainable production of large metal parts without design limitations."

Due to ship in late 2020, the open material system will be capable of building in six qualified metals, including the popular stainless steels 316L, 304L and 17-4PH, as well as in ceramics. The X1 160PRO will also feature Industry 4.0 cloud connectivity and process-linking capabilities enabled by Siemens MindSphere.

The new system also incorporates ExOne's patented Triple Advanced Compaction Technology (ACT) system, said to be critical to delivering consistent part density and repeatability across the entire build area in the Binder Jet process. Triple ACT is reported to tackle the challenges associated with dispensing, spreading and uniformly compacting ultra-fine metal powders, with an average particle size, or D50, of 9 µm.

The X1 160PRO is the tenth and largest metal binder jet Additive Manufacturing system from ExOne

The X1 160PRO joins ExOne's growing family of metal AM systems, which includes the Innovent+, an entry-level system used globally for research, design and small part production, and the X1 25PRO, a mid-size production system which recently began shipping.

www.exone.com

MUT Advanced Heating celebrates its 25th anniversary

MUT Advanced Heating GmbH, headquartered in Jena, Germany, is celebrating its 25th anniversary since it was founded by Heinz-Jürgen Blüm as the MUT company in September 1994. Initially, the company focused on microwave environmental technology before shifting focus to thermal processing plants. It was rebranded as MUT Advanced Heating GmbH in 2003, and has since concentrated on the development of the engineering and production of customised high-temperature furnace technology, both with defined atmospheres and under a vacuum.

MUT believes that its consistent success is due to the systematic implementation of customised approaches to solutions in order to meet higher efficiency requirements and the associated increasing degree of automation in thermal installations. The company's certifications (HPO authorisation, welding fabricator certification) for manufacturing pressure vessels enable it to define the optimal plant selection with its end customers, and guarantee performance on the basis of certified processes.

MUT states that its innovative approaches to thermal process technology are implemented in system solutions in various material sectors, such as ceramics and Powder Metallurgy. The company added that there is continuous interest in the ISO furnace series developed by Blüm.

Due to advancing developments in the fields of materials, energy engineering, and production and process technology, the company recently introduced a new range of AM heat treatment products specifically to meet the demands of the new Additive Manufacturing techniques.

In 2006, together with Element 22 GmbH, Kiel, Germany, MUT founded a joint venture company specifically for the growing titanium technology sector. The TiGen (Titanium Generation GmbH) company is jointly led by H J Blüm and M Scharvogel, CEO of Element 22 GmbH, and specialises in heat treatment and sintering plants for titanium materials and other reactive metals that have been produced by MIM, AM or other forming processes.

"We would like to give a hearty thank you to all our customers, partners, suppliers and employees for the trust and loyalty they have shown to us over past years," the company stated in an anniversary statement. "The entire MUT team is looking forward to a continuation of such reliable and successful cooperation."

www.mut-jena.de

Emery Oleochemicals presents new binder system at Formnext 2019

The Green Polymer Additives team of Emery Oleochemicals, Düsseldorf, Germany, showcased its new binder system for filament-based Additive Manufacturing at this year's Formnext, taking place in Frankfurt, Germany, November 19–22. The binder is designed for use with a wide range of sinterable metal and ceramic powders to create the filament used in Fused Filament Fabrication (FFF).

Emery Oleochemicals began developing its first binder system for the Metal and Ceramic Injection Moulding (MIM and CIM) process in the early 1990s. With the development of metal and ceramic Additive Manufacturing processes, which use filaments made from sinterable feedstock, the company has developed a new binder to target this market.

The filaments contain a high content of metal or ceramic powder, usually greater than 80 wt.%. After the AM build process, the green part undergoes post-processing steps similar to those required in the MIM and CIM process, involving solvent debinding and thermal treatment or sintering.

greenpolymeradditives.emeryoleo.com

MIM and CIM in the spotlight at Formnext 2019 as visitor numbers surge beyond 34,000

A major showcase of more than a hundred components manufactured by MIM and CIM was held at Formnext 2019, Frankfurt, Germany, November 19–22. Organised by *PIM International* in partnership with Mesago Messe Frankfurt GmbH, the 60 m² showcase put PIM technologies in the spotlight at a time when there is high interest in the potential of 'MIM-like' sinter-based AM technologies such as metal Binder Jetting and Fused Filament Fabrication.

The showcase featured parts from Europe, North America and Asia and included award-winning parts from the European Powder Metallurgy Association (EPMA), the Metal Powder Industries Federation (MPIF)'s Metal Injection Molding Association (MIMA), along with numerous application examples from Germany's MIM Expert Group (MIM Expertenkreis) and CIM Expert Group (Expertenkreis Keramikspritzguss). Dr Georg Schlieper, a regular contributor to *PIM International* magazine, was on-hand to speak to visitors about PIM technology and give background information on many of the applications on display.

Whilst the showcase fulfilled its purpose of increasing awareness of the use and potential of PIM, the extent to which a large number of AM-savvy visitors had no awareness of PIM, or worse, a fundamental underappreciation of the capabilities and properties of PIM parts, was surprising. It is inevitable, however, that awareness will improve as a result of MIM producers leading the drive to commercialise sinter-based AM processes as they seek to broaden the range of economically viable applications.

Beyond the PIM showcase, a number of MIM part producing companies were present in the exhibition halls, including Indo-MIM, GKN Sinter Metals, Alliance-MIM, MIMplus Technologies GmbH & Co. KG and MiMtechnik GmbH. Leading MIM-related materials and equipment suppliers were also strongly represented.

Formnext 2019's organisers reported a 28% increase in visitor numbers throughout the four-day event compared to the previous year. According to Mesago Messe Frankfurt GmbH, this year's event was attended by 34,532 visitors and featured 852 exhibitors. Formnext 2020 will be held from November 10–13 in Frankfurt, Germany.

www.formnext.com

Incus reveals novel sinter-based metal AM process based on photopolymerisation

Incus GmbH, a new metal Additive Manufacturing machine maker based in Vienna, Austria, debuted its new metal AM system at Formnext 2019 in November. The company's Hammer Series machine uses a technology based on the principle of photopolymerisation for the Additive Manufacturing of intricate metal components.

This new metal AM technology is said to combine excellent surface aesthetics for fine structures with cost-efficiency, reproducibility and increased manufacturing speed. The process uses a feedstock which is said to increase working environment safety, eliminate the need to invest in protective gas atmosphere solutions, and offer reproducibility without elaborate process parameters.

The company evolved from ceramic AM specialist Lithoz GmbH. "Our goal is to become an integral part of production in the metal industry. To achieve this, we are focusing on absolute service orientation and our passion for bringing innovative metal printing solutions to market. Quality and partnership are cornerstones of our business model," stated Dr Gerald Mitteramskogler, CEO of Incus.

According to Incus, metal Additive Manufacturing technologies currently on the market offer the production of parts using relatively coarse metal powders in the range of around 40–100 µm. With the new Incus process, it is possible to use metal powders down to 20 µm at competitive build speeds.

Mitteramskogler further added, "With our new printer series, it is not only possible to produce very small complex components with the finest surface structure, it also allows us to use new metal powder mixtures, such as non-weldable powders. In material development projects with our customers, we have already shown that we can achieve similar material properties compared to MIM."

Two beta machines are reported to have been in use for development for over a year, and feasibility studies have shown that the expectations for the technology are being met. Prof Carlo Burkhardt, Head of the Institute for Strategic Technology and Precious Metals at the University of Pforzheim and founder of local company MetShape, who has been involved in the development of applications for the new systems, stated, "We are always intrigued by cutting-edge technologies and are convinced that we are part of a new era in the metalworking industry. The components we produced in the beta phase with the printer exceeded our expectations."

www.incus3d.com

First components produced with the Incus Hammer series (Courtesy MetShape/Incus)

JPMA award for MIM industrial robot component

A Japan Powder Metallurgy Association (JPMA) 2019 'Effort Prize' was awarded to Fine Sinter Co. Ltd. for the development of a metal injection moulded component used in an industrial collaborative robot. The part requires high accuracy, to less than 0.1% of the nominal dimension, high strength and high corrosion resistance, which had originally led to machined stainless steel being used.

A metal injection moulded component used in an industrial collaborative robot produced by Fine Sinter Co. Ltd. (Courtesy JPMA)

The conversion to MIM had the potential to save material and reduce cost. To manufacture the parts to such a high tolerance, conventional process routes would require a final machining stage. However, the design freedom of the MIM process allowed unnecessary part thicknesses to be reduced, with strengthening ribs introduced as needed. This reduced the overall amount of machining, compared with a fully machined part, by 80–90%.

The market for industrial collaborative robots is expected to grow in the near future due to the increasing need for automation. Offering total cost savings of around 70–80%, MIM has now been adopted for the production of these components.

A full listing of all 2019 JPMA Award winning components is published in the Winter 2019 issue of *PM Review*.

www.fine-sinter.com
www.jpma.gr.jp

Admatec launches Admaflex 300 system for production of large-scale parts

Admatec Europe BV, Goirle, the Netherlands, has launched the Admaflex 300, which it states is the world's first flexible and open system for high-volume metal and ceramic additively manufactured parts. The system was showcased at Formnext 2019, Frankurt, Germany, from November 19–22.

According to the company, the Admaflex 300 is designed with openness and flexibility in mind, enabling the user to expand their system for additively manufacturing metal parts on the same machine. This modular concept also provides the opportunity for the customer to develop their own material, set up a customised build process and have full control over it.

Future developments such as multi-material Additive Manufacturing can reportedly be accommodated thanks to the modularity of the machine's concept, as it is capable of handling feedstocks with a broad range of viscosities.

The new machine offers integrated in-process quality monitoring for full traceability of the Additive Manufacturing process, with software and hardware components monitoring temperature, humidity and foil usage. It also has a dual-camera system for real-time video capture, and time-lapse recording which allows the user to partially halt the AM of a defective product to allow the successful finalisation of the remaining parts.

Admatec launches new AM system, the Admaflex 300, which was showcased at Formnext 2019 (Courtesy Admatec Europe BV)

"Our customers' feedback led to the development of an increased build platform size, enabling the investment casting industry, among others, to expand their ceramic 3D printing capabilities," stated Jaco Saurwalt, COO at Admatec.

admateceurope.com

ExOne and GTP to advance Binder Jet AM of tungsten parts

The ExOne Company, North Huntingdon, Pennsylvania, USA, has entered into a collaboration with Global Tungsten & Powders Corp. (GTP), headquartered in Towanda, Pennsylvania, USA, a supplier of tungsten and molybdenum powders, semi-finished parts and SOFC components, to advance tungsten-based binder jet Additive Manufacturing.

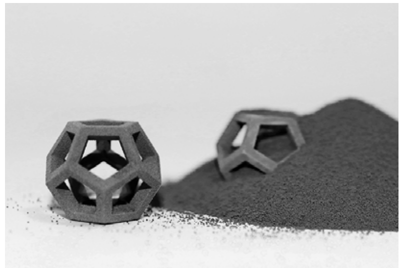
The collaboration will reportedly focus on the development of two metal matrix composites including:

- Cemented carbide (WC-Co), a material with very high hardness and toughness that is widely used for the production of cutting tools and wear-resistant parts
- Copper-tungsten (CuW), which is used in applications where high heat resistance, high electrical and thermal conductivity, and low thermal expansion are required

Under the collaboration, GTP will launch an Additive Manufacturing and sintering service for cemented carbide parts which can be used by customers that wish to explore the feasibility of new designs. GTP currently uses the ExOne® Innovent®, a Binder Jetting system for the AM of metal, ceramic and composite powders in a compact build area.

"Binder Jetting is the 3D printing method of choice for serial production of hard metal parts," stated Deborah West, Vice-President Business Unit Refractory & Specialty Powders, GTP. "Traditionally, tungsten carbide powder is pressed into the desired shape and then sintered to give it strength and density. Instead of costly and timely mould construction, the parts now can be printed directly in the desired shape, still using sintering technology to achieve the final strength."

"As a market leader in the development and production of high-quality tungsten powders, GTP always stays on top of the latest technology," West continued. "We are excited to work with ExOne in the development of cutting-edge technology for the Additive Manufacturing industry."



The ExOne Company and Global Tungsten & Powders Corp. hope to advance the AM of tungsten parts (Courtesy The ExOne Company)

Tim Pierce, ExOne's Vice President of Metal Commercial Products, commented, "Metal 3D printing using our exclusive approach to Binder Jetting has exciting and significant consequences for a variety of manufacturers, including those who make parts with cemented carbide and other tungsten composites. Our latest development collaboration with GTP will help advance the materials necessary to deliver on the vision of producing these parts faster, with less waste and more geometric design freedom."

www.exone.com
www.globaltungsten.com

Digital Metal announces agreement with Elnik Systems/DSH Technologies

Digital Metal, part of the Höganäs Group and a producer of metal binder jet Additive Manufacturing machines, has formed a collaborative agreement with debinding and sintering experts Elnik Systems/DSH Technologies, LLC. The process optimisation services of Elnik Systems/DSH Technologies are expected to benefit existing and future customers of Digital Metal in terms of optimised recipe/profile development parameters to ensure successful results.

Combining Höganäs' 100+ years of knowledge in metal powder fabrication and the expertise of Elnik/DSH Technologies in debind and sinter technology, Digital Metal stated that with this agreement, it is taking the next step to deliver real-world solutions to its existing and future customer base. Stefan Joens, Vice President, DSH Technologies, LLC, stated, "We are excited to team up with the Digital Metal team to help advance the newest and most exciting metal manufacturing technology in decades!"

Christian Lönne, General Manager, Digital Metal, added, "Learning and exploring together with the curious and highly-experienced people at Elnik Systems/DSH Technologies LLC means that we together can provide even higher consistency and stability, as well exploring new fields for our fast-growing customer base."

www.digitalmetal.tech

www.elnik.com

Desktop Metal launches new mid-size metal Binder Jetting system

The press launch of the Shop System at Formnext 2019

Desktop Metal, Burlington, Massachusetts, USA, announced its new Shop System™, a metal Binder Jetting system designed for machine shops and metal job shops, at Formnext 2019, Frankfurt, Germany. Beginning at $150,000, the high-speed, single-pass system is said to introduce high-quality metal Binder Jetting to a new market of machine shops and metal fabrication job shops, a global industry estimated to be worth nearly $180 billion.

According to Desktop Metal, the Shop System offers an end-to-end solution, including the AM machine, powder station and furnace, which integrates with existing shop operations. It can be used to additively manufacture end-use metal parts that span 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.

It is reported to be able to produce parts up to ten times faster than L-PBF and at a fraction of the cost-per-part. The Shop System can manufacture a batch of complex parts every six to twelve hours, enabling from tens up to hundreds of near-net shape metal parts to be produced each day, says Desktop Metal.

At the machine's announcement, the company explained that parts produced on its Shop System are built fully supported in a powder bed and feature hand-removable sintering setters. This, it was stated, could enable users to avoid hours of labour machining or wire EDM to remove support structures; reducing the total number of manufacturing steps needed and increasing shop productivity and capacity without requiring additional headcount or machinist hours.

Jonah Myerberg, co-founder and CTO of Desktop Metal, stated, "Shop owners have been enamoured by the versatility, speed and cost reduction that Binder Jetting technology can provide, but until now, it hasn't been accessible to them. The Shop System offers users the same fully-dense metal parts at an affordable price that works in harmony with machining on the shop floor. What's more, the system enables owners to both save and make money by eliminating tooling costs, lowering lead times, and bringing in new business because of an improved part-cost equation."

The system utilises a spot size of 16 µm per drop, 1600 native single pass DPI and distributes up to 670 million drops per second. It is said to offer the smallest droplet size for single-pass Binder Jetting systems at approximately 1 pL, and automated drop multiplexing up to 6 pL. Desktop Metal added that the system's 70,000 nozzles per line have built in five times redundancy to help to avoid jet-outs, resulting in enhanced quality and reliability for shop owners. It is available in variable configurations, from 4 to 16 litres.

www.desktopmetal.com

Markforged to double AM machine production capacity with new facility

Markforged, Watertown, Massachusetts, USA, has opened a new manufacturing facility in Billerica, Massachusetts. The facility is expected to enable the company to more than double its Additive Manufacturing machine production capacity, supporting increased demand for its metal AM and carbon fibre AM systems.

This is the third major footprint expansion for the company in 2019. Earlier this year, it announced the opening of its European headquarters in Dublin, Ireland, as well as an artificial intelligence innovation centre in Cambridge, Massachusetts.

According to Markforged, demand for its materials and systems has "exploded" in recent years, with its material production increasing by 81% in twelve months. The new facility is expected to support the fabrication of all Markforged materials, which are used by companies in aerospace, automotive and manufacturing.

"With the significant growth of Markforged printers in the field, the consumption of our materials continues to increase at a rapid pace. Our new facility in Billerica gives us the ability to meet the demands of today and operations for years to come," stated Matt Gannon, the company's Vice President of Operations. "Billerica was the perfect choice for our expansion. The region is a hotbed for manufacturing and technology companies, and is strategically located with access to key partners and expertise to support the team."

www.markforged.com

Markforged's new production facility in Billerica, Massachusetts (Courtesy Markforged)

Ceramitec conference: a successful first edition

The organisers of the ceramitec conference, a new addition to the ceramitec event portfolio, have reported a successful first edition for the event, which saw more than 200 participants from twenty-one countries in attendance in Munich, Germany, from September 19–20, 2019. Organised by Messe München, the two-day conference focused on new industrial use opportunities for ceramic and ceramic AM processes, as well as PM, with key speakers from academia and industry.

In particular, the speakers discussed how the use of ceramic can help to solve a range of future challenges in the automotive, aerospace, electronics, manufacturing and health sectors. The programme was divided into two conference tracks, 'Shape the Future', an AM-focused track and a continuation of the AM Ceramics conference series previously held in Vienna and Nuremberg, and 'Industrial Applications', examining new uses for high-performance ceramics in industry.

Johannes Homa, CEO of Lithoz GmbH, commented, "AM has now definitely found its place in ceramic production as more and more companies are recognising the potential of this process. AM Ceramics integrated into the ceramitec conference offered an ideal platform to present the extensive range of application opportunities and their benefits."

www.ceramitec.com

Indo-MIM accelerates move to offer metal Binder Jetting

Indo-US MIM Tec Pvt.Ltd, a leading global manufacturer of components by Metal Injection Moulding, headquartered in Bangalore, India, reports that from January 2020 it will be accepting prototype/sample orders for parts produced on its installed Production System, the high-volume metal binder jet solution from Desktop Metal, Burlington, Massachusetts, USA.

Indo-MIM states that it is initially offering two material choices, 17-4 PH and 316L stainless steels, with more material options expected to be added by Summer 2020. Prototype samples are offered within ten days and series production volumes are stated as being between 10 and 50,000 parts per year, with plans to increase to production volumes of up to 500,000 by 2021. Suitable part weights are given as 5–250 g.

Indo-MIM has MIM production facilities in both India and the USA, as well as further sales offices in Europe and Asia. The company is deploying its metal Additive Manufacturing capability from its San Antonio, Texas, operation.

www.indo-mim.com

EPMA PM Component Awards 2020

The European Powder Metallurgy Association (EPMA) has opened submissions for its Powder Metallurgy Component Awards 2020, which will coincide with the Euro PM2020 Congress & Exhibition in Lisbon, Portugal, October 4–7, 2020.

The awards competition is designed to promote interest in PM technology and is open to all companies which manufacture components by PM processes. The 2020 awards will be given in component categories that include PM structural parts (including hard materials and diamond tools parts), AM, HIP and MIM. A panel of independent experts, drawn from across Europe, will judge all entries by the following criteria:

- To what extent will the component deliver cost savings and/or improved quality?
- To what extent is the entry expected to stimulate further usage of PM?
- How well is the entry prepared?
- How well does the component exploit PM and how innovative is it?

The submissions deadline for the EPMA Powder Metallurgy Component Awards 2020 is May 27. Further information on the awards and submission guidelines is available via the organiser's website.

www.componentawards.epma.com

Construction begins on Höganäs' new powder atomising plant

Sweden's Höganäs AB has begun constructing its new atomising plant for the production of high-purity metal powders for the Additive Manufacturing industry. The powders produced will be sold globally under the trademark Amperprint®.

The plant is based at the Laufenburg production unit in Germany and completion is scheduled for the third quarter of 2020. The Freiburg Regional Council is said to have approved the construction and operation of the plant under the conditions of the German Federal Emission Control Act (BImSchG) in September.

Currently, Höganäs has a yearly metal powder production capacity of 500,000 tons. The company operates eighteen production centres worldwide and has a workforce of 2,500 employees.

"The investment in the million-euro plant will help us to significantly increase our market share for metal powders in the promising segment of 3D printing," stated Peter Thienel, Höganäs' Site Manager. "In addition, we want to further increase the attractiveness of Höganäs as an employer in Germany and are confident that we can continue to offer our co-workers long-term professional development."

www.hoganas.com

Asiamold 2020 set for February

Asiamold 2020, organised by Guangzhou Guangya Messe Frankfurt Co Ltd., will be held at the China Import and Export Fair Complex in Guangzhou, China, from February 26–28, 2020. The event will be held concurrently with SPS – Industrial Automation Fair Guangzhou (SIAF), and will bring together leading brands in the tool, die and moulding industries and cover a diverse range of metalworking technologies.

In line with China's rapid development in the field of AM, the 3D Printing Asia Zone will once again feature as a key highlight of the show. Additionally, the three-day event will showcase other thematic zones including Asiametal, Foundry and Die-casting as well as Laser and Welding Asia and Asiabearing. These various zones will assist manufacturing industry professionals with their sourcing needs and showcase the entire process chain.

The 2019 edition of Asiamold, together with SIAF, saw more than 98,000 visitors and over 900 exhibitors from twenty countries occupy its five halls across 62,000 m^2 of exhibition space. Asiamold 2020 forms part of a series of international events including Formnext, Intermold Japan, Rosmould and Formnext + PM South China.

www.asiamold-china.cn.messefrankfurt.com

GKN and Volkswagen on the way to mass production with HP Metal Jet

In 2018, Volkswagen Group selected the HP Metal Jet as the foundation for its strategy to industrialise Additive Manufacturing as part of a multi-year design and production roadmap. Working with HP Inc. and GKN Powder Metallurgy, it has now reached a key milestone in the first stage on its route to functional production.

To support VW's ID.3 electric vehicle launch event, a production run of 10,000 promotional model vehicles has been completed by HP and GKN using the HP Metal Jet system, over the course of a few weeks. Volkswagen reported that this latest production run marks a significant step in its three-phase strategic roadmap.

Dr Martin Goede, VW's Head of Technology Planning and Development, stated, "Our vision to industrialise Additive Manufacturing is quickly becoming a reality with HP Metal Jet, it is a game changer for the automotive industry. The pace of innovation by HP and advanced capabiltiies of the technology have exceeded our expectations. We are meeting our milestones and are actively identifying and developing functional parts for production."

VW's strategic roadmap for Metal Jet production begins with mass customisation and cosmetic parts. In subsequent phases of its plan, VW intends to integrate structural parts produced on the HP Metal Jet into the next generation of vehicles, and is targeting a continuous increase in part size and technical requirements – with the future goal of producing parts in runs of 50,000 to 100,000 parts per year.

Examples of higher performance functional parts with structural requirements include gearshift knobs and mirror mounts. As new platforms such as electric vehicles enter mass production, HP Metal Jet technology is expected to be employed for additional applications such as the lightweighting of fully safety-certified metal parts.

"A digital transformation in the auto industry is underway and Volkswagen is leading the way with strategic vision and bold action," commented Tim Weber, Global Head of Metals, HP 3D Printing and Digital Manufacturing. "We are committed to delivering the capabilities our customers need to accelerate the design and production of high-quality final parts with breakthrough economics. Together with Volkswagen and partners like GKN, we are standing up the factories of the future."

www.hp.com/go/3Dprinting
www.gknpm.com
www.volkswagen.com

Euro PM2019: EPMA Fellowship, Distinguished Service Awards and Thesis Competition winner announced

The European Powder Metallurgy Association (EPMA) announced the recipients of its annual Fellowship Award, Distinguished Service Award and Thesis Competition at the Euro PM2019 Congress & Exhibition, in Maastricht, the Netherlands, October 13–16, 2019.

The EPMA Board and Council's Fellowship Award recognises individuals in the scientific and/or academic community for significant contributions to the development of the PM industry. The two recipients of the 2019 Fellowship Awards were Professor Francisco Castro and Professor Dr-Ing Bernd Kieback.

Before becoming a PM industry consultant, Professor Castro was a Principal Senior Researcher at Spain's CEIT, being the director of the Materials and Manufacturing Division. Professor Kieback is Chair Powder of Metallurgy & Composite Materials, Technische Universität Dresden, Institute of Materials Science, and Fraunhofer Institute for Manufacturing and Advanced Materials IFAM Dresden.

The 2019 Distinguished Service Award was presented to Dr-Ing Ingo Cremer, CEO, CREMER Thermoprozessanlagen GmbH, Düren, Germany.

The annual EPMA Thesis Competition award was presented to Dr Chu Lun Alex Leung, from the University of Manchester, UK, for his paper on the 'X-ray Imaging of Powder Consolidation During Laser Additive Manufacturing'.

Euro PM2019 covered all aspects of Powder Metallurgy, and featured a congress programme of over 300 technical papers, in addition to the parallel Euro PM Exhibition, featuring more than 100 exhibiting companies.

www.europm2019.com

EPMA President Ralf Carlström presented the awards. Top left: EPMA PM Thesis Competition 2019 winner - Doctorate/PHD Category - Dr Chu Lun Alex Leung (centre) with Euro PM2019 TPC Co-Chair Prof Jie Zhou. Top right: EPMA Distinguished Service Award 2019 Winner, Dr-Ing Ingo Cremer. Bottom left: EPMA Fellowship Award Winner 2019 - Prof Francisco Castro. Bottom right: EPMA Fellowship Award Winner 2019 - Prof Dr-Ing Bernd Kieback (Courtesy EPMA)

Metal Powder Industries Federation elects new president

Dean Howard has been elected as MPIF President (Courtesy MPIF)

Dean Howard, PMT, President of North American Höganäs Co., a subsidiary of Höganäs AB, Hollsopple, Pennsylvania, USA, has been elected the 30th president of the Metal Powder Industries Federation (MPIF), succeeding John F Sweet, PMT, FMS Corporation, Minneapolis, Minnesota, USA. His two-year term began at the conclusion of the Federation's annual Powder Metallurgy Management Summit and 75th Annual MPIF Business Meeting, October 26–28, 2019, in Miami, Florida, USA.

Howard has worked for North American Höganäs Co. for nearly twenty years. He most recently served as president of the MPIF's Metal Powder Producers Association (MPPA), and has served the association actively for many years, receiving the MPIF's Distinguished Service to Powder Metallurgy Award at POWDERMET2017.

He has also been a member of APMI International for twenty-six years, and has served as Chairman of APMI's Southeast Chapter and as APMI International President (2010–2014). He received certification as a Level I Powder Metallurgy Technologist in 1998.

The MPPA also instated a new president following the summit. Jill Spaulding, Kymera International, Research Triangle Park, North Carolina, USA, will serve a two-year term as the association's president.

www.mpif.org

LÖMI launches debinding systems dedicated to sinter-based AM

LÖMI GmbH, Grossostheim, Germany, has launched a new system solvent debinding series, EDA-AM, to meet the increasing demand from the Additive Manufacturing industry. The company states that the three systems in the series offer three-in-one functionality by integrating debinding, the drying of parts and solvent recovery. This is said to save time and cost, as no additional handling of the parts is required between the debinding and drying process steps, while the integrated solvent recovery ensures a continuous supply of fresh debinding medium.

LÖMI's smallest AM solvent debinding system, EDA-30, is a tabletop unit with 16 litres batch loading volume for research, prototyping and small batch production. It is water-cooled and offers basic automation. The two larger systems EDA-30AM and EDA-50 both feature integrated tanks for the clean and used debinding solvent. The EDA-30AM is a semi-automatic air-cooled system with 16 litres batch loading volume, while the water-cooled EDA-50 offers 26 litres batch loading volume and full automation. It is PLC-operated, and a touch display shows real-time process parameters to facilitate process control.

"The solvent debinding process offers a number of advantages including a greater freedom of feedstock choice for AM part producers, as a wide range of feedstock can be processed," explained Christian Ferreira Marques, Managing Partner at LÖMI. "This enables part producers to test new feedstock and to optimise their processes, without having to invest in another debinding system and without becoming dependent on a single feedstock producer."

LÖMI introduces debinding series EDA-AM specifically for AM industry (Courtesy LÖMI)

Ferreira continued, "In addition, various organic solvents can be employed, such as ethanol, isopropanol and acetone. Solvent debinding systems offer very compact dimensions and are very economical in their operation due to their low energy consumption and very long lifetime, as the solvent debinding process causes very little wear and tear. The solvent is continuously reprocessed with a rate of up to 99% and returned to the process in a closed system. This makes our systems very safe and environmentally beneficial."

www.loemi.com

Aperam and Tekna establish new metal powder company ImphyTek Powders

Aperam S.A., Luxembourg, and Tekna, a subsidiary of Arendals Fossekompani ASA with its headquarters in Sherbrooke, Canada, have approved the framework of a global joint venture which will combine their expertise to create nickel and speciality alloy spherical powders through a newly-established company ImphyTek Powders™ SAS.

Aperam is a global provider of stainless, electrical and speciality steel, and is organised across three primary segments: Stainless & Electrical Steel, Services & Solutions and Alloys & Specialties. The company has 2.5 million tonnes of flat stainless and electrical steel capacity in Brazil and Europe. In 2018, it reported sales of €4,677 million and steel shipments of 1.97 million tonnes.

Tekna develops and produces high-purity metal powders for applications such as AM and microelectronics, as well as optimised induction plasma systems for industrial research and production. The company has manufacturing centres in Canada and France, as well as sales and distribution offices in China, India and South Korea.

The formation of the new joint venture results from an earlier Memorandum of Understanding (MoU) agreed by the companies in 2018, in which Tekna and Aperam partnered to develop high-quality spherical powders for metal AM and Metal Injection Moulding.

ImphyTek Powders SAS will be based in France and market Aperam and Tekna's jointly-developed metal powders to the AM and MIM industries.

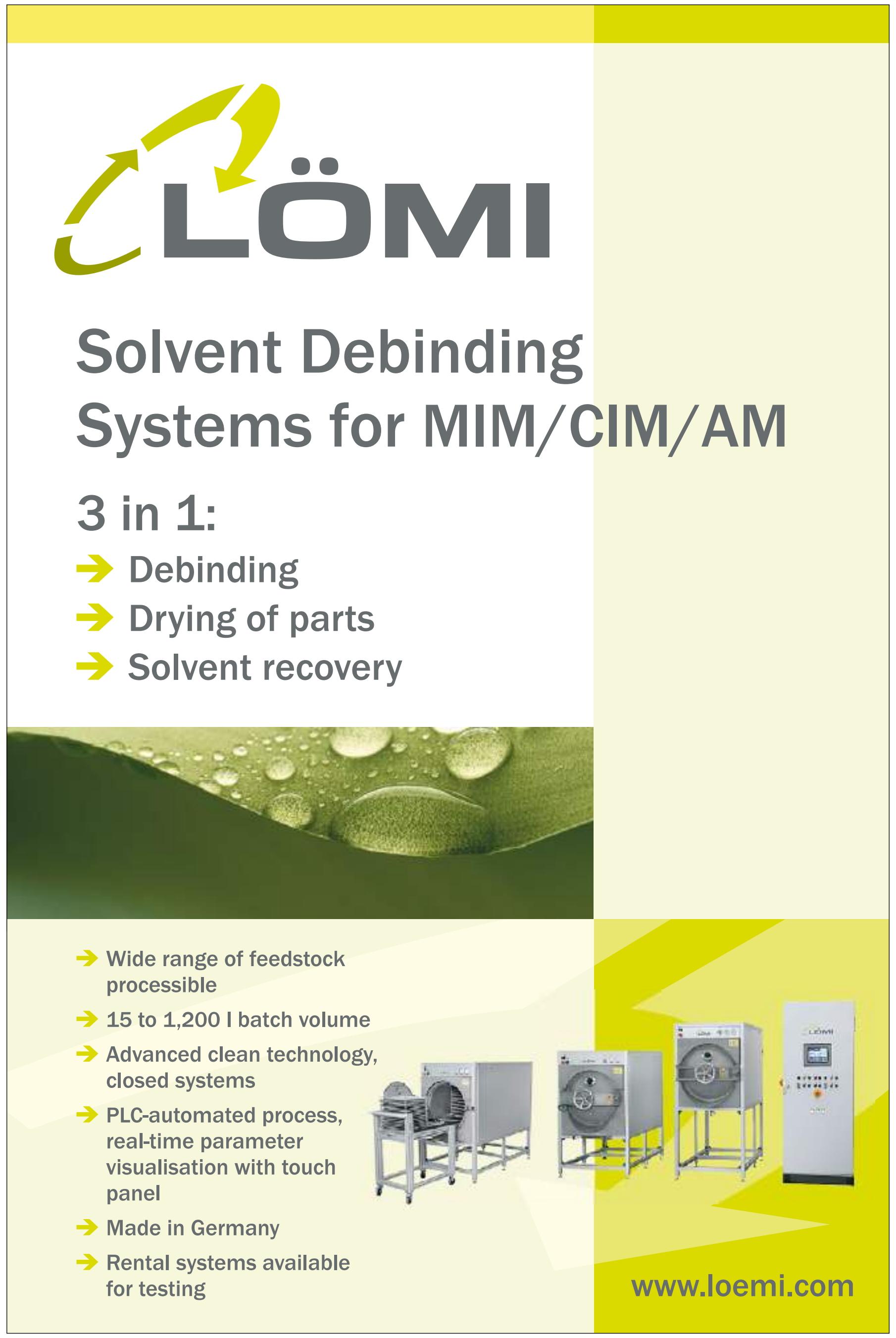
www.aperam.com
www.tekna.com

Carpenter year-on-year growth

Carpenter Technology Corporation, Philadelphia, Pennsylvania, USA, has announced financial results for its fiscal first quarter ended September 30, 2019. The company reported Q1 2020 net income of $41.2 million, a significant increase from $31.5 million in Q1 2019. Net sales for Q1 2020 were $585.4 million compared with $572.4 million in the first quarter of fiscal year 2019.

The Performance Engineered Products (PEP) division, which includes Carpenter's Dynamet titanium business, Carpenter Powder Products business, Amega West and Carpenter Additive, reported net sales of $109.4 million, down slightly from $111.7 in Q1 2019.

www.carpentertechnology.com



Liberty Powder Metals begins construction of new atomiser facility

Liberty House Group, parent company of Liberty Powder Metals, Sheffield, UK, has begun construction of a powder metals development facility in Teesside, UK, which it hopes will enable the group to expand its reach in specialist metals and materials.

The new powder metals facility will be based at the Materials Processing Institute in South Bank, Middlesbrough, UK, and an initial £10 million is also being invested to establish the Liberty Powder Metals business in this location. This investment will include a state-of-the-art vacuum induction inert gas atomiser (VIGA), for which Liberty Powder Metals secured funding from the Tees Valley Combined Authority Cabinet, UK. There are also plans to install a range of sieving, blending, packaging and analytical equipment at the facility.

It was stated that the atomiser will enable the group to develop a new generation of powdered steels and enhance its position in the supply chain for precision steel components used in rapidly-changing and advanced sectors such as aerospace, automotive, energy and specialist industrial equipment.

Dr Simon Pike, General Manager of Liberty Powder Metals, stated, "We are grateful to our partners for the work they have done to reach this stage. Finance from Tees Valley Combined Authority has been critical in making the project a reality and I look forward to continuing all our partnerships to make Teesside a global-leading centre of expertise for powder metal production."

"We are glad to see construction now starting," commented Chris McDonald, Chief Executive Officer for the Materials Processing Institute. "Advanced materials development is a core area of research at the institute and this investment by Liberty Powder Metals is an example of the benefits of partnerships and collaborations between industry and the Institute."

Tom Sellers, Commercial and Business Development Manager for Liberty Powder Metals, added, "We are excited about the progress to date and I am looking forward to bringing our products to market and developing our customer base along with the strength of the Liberty brand."

Atomising Systems Ltd and Consarc Engineering designed the equipment for the powder metals facility, while K-Home International is managing the installation at the Materials Processing Institute.

www.libertyhousegroup.com
www.atomising.co.uk

Engel and Autodesk showcase Engel sim link software for injection moulding process at K 2019

Injection moulding machine manufacturer Engel Austria GmbH, Schwertberg, Austria, announced during K 2019, Düsseldorf, Germany, that it is collaborating with Autodesk, Inc, San Rafael, California, USA, to further develop the digitalisation of the injection moulding process.

As part of the collaboration, the companies have developed the new Engel sim link, which will reportedly be available to Engel and Autodesk customers next year. According to Engel and Autodesk, the Engel sim link makes it possible to transfer simulation data to the injection moulding machine and – conversely – to import measurement datasets from the machine control unit to the simulation software.

The companies state that the aim is to link the simulation with the real process, in order to be able to better support manufacturers throughout the complete product life cycle – from product development and tool design through to production. The Engel sim link will reportedly show the results of simulations performed using the Moldflow simulation software from Autodesk which can be transferred to the CC300 control of the Engel injection moulding machine – and how process and measurement data can flow back from the machine for use in the simulation.

An additional new feature is that process parameters and measurement results can conversely be imported from the injection moulding machine back into Moldflow. The companies explain that this function opens the door to a completely new approach to the analysis and optimisation of the ongoing production process using simulations. Simulation and measurement data can be easily reconciled, and the quality of the simulation improved.

Engel Austria and Autodesk showcase its collaborative Engel sim link software at trade show K2019 (Courtesy Engel Austria GmbH)

Furthermore, with support provided by simulations, unfavourable process settings can be subjected to in-depth analysis and, therefore, adaptations implemented more rapidly and precisely.

"Together with Autodesk we are closing the gap between the digital twin of the actual tool and the real injection moulding process," reported Dr Johannes Kilian, Head of Simulation and Control Engineering at the Product Development Department of Engel Austria. "By creating easily usable connections between the digital and the real world we are facilitating the consistent and mutual utilisation of simulation and machine data throughout the complete product life cycle."

Kilian added, "By linking the simulation with the real production process, injection moulding simulations will in future play a central role throughout the entire product life cycle. Simulations accelerate the machine setting, set-up processes and process optimisation, thereby significantly boosting productivity. It is therefore becoming an increasingly affordable competitive advantage for smaller injection moulding companies too."

www.engelglobal.com
www.autodesk.com

EPMA issues Call for Papers for Euro PM2020

The European Powder Metallurgy Association has issued a Call for Papers for its Euro PM2020 Congress & Exhibition, which will take place in Lisbon, Portugal, October 4–7, 2020. Abstract submissions are invited for presentation in the technical programme, and will reportedly be allocated to either oral or poster sessions by the Technical Programme Committee (TPC) based on authors' wishes, the committee's evaluation and the limits of the time schedule.

Each oral session on the programme will contain four presentations, with twenty-minute slots for each paper, including discussion time. Poster presentations will be placed in allocated topic zones and will be displayed for the duration of the four-day event.

Abstracts for Euro PM2020 are invited on the following topics:

- Additive Manufacturing
- Functional materials, PM magnetic materials, porous materials
- Hardmetals, hard materials, cermets and diamond tooling
- Hot Isostatic Pressing
- PM applications, materials and processes
- Powder Injection Moulding
- Modelling and simulation
- Non-destructive testing,
- Powder manufacturing and processing
- Powder pressing, secondary and finishing options
- Sintering

Authors are invited to submit their abstracts using the EPMA's online submission form by the deadline of January 22, 2020. Further information is available via the organiser's website.

www.europm2020.com

The EPMA has confirmed that Euro PM2020 will take place from October 4–7 in Lisbon, Portugal

Ipsen USA expands its aftermarket service by employing five regional sales engineers

Ipsen USA, Cherry Valley, Illinois, USA, has expanded its aftermarket service coverage across the US and Canada by hiring five regional sales engineers (RSEs) to assist customers with replacement parts, retrofits, upgrades, service and technical support for any brand of atmosphere or vacuum heat-treating system.

According to the company, the RSEs will fill a crucial role by creating a more efficient system for managing customer needs and streamlining the process between new equipment sales, aftermarket service, and field support. The RSEs reportedly offer a range of experience in engineering, machine repair and metallurgical processes.

They are supervised by Matt Clinite, Ipsen Customer Service Sales Manager, who stated, "Our team is here to identify risk points with our customers' equipment. Our goal is to help our customers better prepare for maintenance planning and experience maximum furnace up-time and reliability."

www.ipsenusa.com

Plansee to construct new sintering facility and training centre

Plansee Group, headquartered in Reutte, Austria, is investing in a new sintering facility and has begun construction of a new €6 million training centre. According to the group, the new sintering facility is the culmination of many years of preparation, including the development of new processes and technologies reported to have been extensively trialled in test facilities. Its engineers are said to have been particularly keen to reduce the volume of raw materials it uses, increase material quality, and reduce sources of errors through automation in order to make production faster and more reliable.

Another focus of the development is said to be to save energy. To achieve this goal, hydrogen used in the sintering equipment at the new facility is to be recycled and the cooling water to be used to heat other parts of the factory.

The ground-breaking ceremony for the new sintering facility took place in September. Although the group has not yet confirmed any further information, Plansee reports that it is investing several tens of millions of euros in the new plant, along with all the associated equipment and new technological developments. Ulrich Lausecker, Plansee's Managing Director, commented, "Construction of our new sintering plant will allow us to elevate our production to a new level of quality and to save energy and material."

New training centre

The new €6 million training centre is located in Breitenwang, Austria. Once completed, the 3,000 m^2 centre will allow up to 240 people to receive training in a variety of metalworking professions. According to the company, construction is scheduled to take one year, with the centre expected to be operational as of the beginning of the academic year in September 2020. The vocational school at Plansee will also be expanded, with new classrooms and IT rooms being added, as well as laboratories for hydraulics, pneumatics and electrical engineering to accommodate a growing number of students.

"We see a growing need for well-trained specialists, and the construction of our new training workshop sets us up for taking on up to sixty apprentices each year," stated Bernhard Schretter, Member of the Executive Board of the Plansee Group. Currently, forty apprentices are being taken on each year by the company. "We will continue to train apprentices for our own needs in the future," Schretter added.

In addition to job-specific theoretical and practical skills, vocational training at Plansee places great emphasis on personal development, including a range of teamwork and projects. Schretter added, "We have been following a path of combining careers and apprenticeships for decades. Many of our longstanding, seasoned managers started their careers with an apprenticeship at Plansee and Ceratizit."

Plansee and Ceratizit currently offer apprenticeships for metallurgical technicians with cutting technology and mechanical engineering as the primary modules, process technician, materials engineering technician, electrical engineer, chemical laboratory technician, office administrator and information technologist.

www.plansee.com

PMAI announces dates for its PM20 Conference in Mumbai

The Powder Metallurgy Association of India (PMAI) has announced dates for its International Conference on Powder Metallurgy and Particulate Materials & Exhibition 2020 (PM20).

The event will take place from February 19-21, 2020 at The Lalit Mumbai, Sahar Airport Road, Andheri East, Mumbai, India, and will once again combine a technical programme and an international trade exhibition. PM20 will also include the 46th Annual Technical Meeting of PMAI.

www.pmai.in

GKN Powder Metallurgy sales dip due to General Motors strike, expands AM presence

Melrose Industries PLC, UK, has published a trading update for its third quarter, July 1 to October 31, 2019, in which it states that its GKN Powder Metallurgy division was impacted by the temporary effects of the General Motors strike, leading to a sales decline of 13% when compared to the same period last year. However, the company stated that, without the strike, revenue would have been in line with the Board of Directors' expectations.

Melrose confirmed that during the trading period, contracts were exchanged to acquire Forecast 3D, an Additive Manufacturing company specialising in plastics, which had sales of $19 million in 2018. The acquisition is expected to complete by the year end and will reportedly further expand GKN Powder Metallurgy's capabilities in this growing market.

The GKN Aerospace division was reported to have achieved sales growth of over 5% in the quarter, compared to the same period last year, outperforming the board's expected longer term average growth rate. In addition, good margin improvement has been delivered compared to the same period last year.

GKN Automotive also delivered a higher profit and margin in the period compared to the same period last year. Sales were reported to be down 5% year-on-year, however, which also included the temporary effect of the General Motors strike in the USA.

Melrose stated that group net debt was in line with the board's expectations, with significant investment and restructuring actions being funded to further improve performance and initial steps to reduce working capital in GKN being implemented as planned.

Justin Dowley, Chairman of Melrose, stated, "Melrose continues to do what it has always done well: improve businesses. Some macro conditions could be more helpful, but this has not stopped us continuing to transform the GKN businesses, delivering another trading period in line with expectations, and achieving better trends than seen in the first half of the year. We are excited about what is possible and confident in our ability to unlock significant further shareholder value."

Melrose acquired GKN plc, including GKN Powder Metallurgy, the world's largest producer of Powder Metallurgy components, for £8.1 billion in April 2018.

www.gknpm.com
www.melroseplc.net

Gammatec Engineering receives Fachmetall PM Qualification Award 2019

Gammatec Engineering GmbH, Radevormwald, Germany, has received the Fachmetall PM Qualification Award 2019 for outstanding services to the Powder Metallurgy industry. Dr Georg Schlieper, General Manager of Gammatec, was presented with the award by Holger Davin and Dr Evelyne Gonia of Fachmetall GmbH, Radevormwald, Germany.

Dr Schlieper has served the PM industry for the majority of his professional life; starting as an engineer, he worked in R&D for high-strength sintered steels, soft magnetic PM materials and the emerging Metal Injection Moulding technology. He is credited with the design and launch of the Gamma Densomat, a non-destructive measuring device for the sectional density of metallic and ceramic components.

In 2012, Dr Schlieper founded Gammatec Engineering GmbH, marketing the Gamma Densomat as well as products for industrial furnaces and other high-temperature applications, in molybdenum, tungsten, tantalum and engineering ceramics. Additionally, he regularly reports on company visits, technical conferences and trade exhibitions for *Powder Injection Moulding International*, *Metal Additive Manufacturing* and *PM Review* magazines.

Fachmetall GmbH is a metallurgical laboratory specialising in investigations of Powder Metallurgy and wrought materials. Its annual 'Powder Metallurgy Qualification Award' and the 'QM Context Award' aim to promote companies for their outstanding Powder Metallurgy and quality management activities.

From left to right: Dr Georg Schlieper with Dr Evelyne Gonia and Holger Davin of Fachmetall GmbH (Courtesy Fachmetall GmbH)

www.gammatec.com
www.fachmetall.de

Ti-6Al-4V parts using lower-cost blended powders

Powder	O (wt.%)	C (wt.%)	N (wt.%)	Price (USD/kg)
GA Ti	0.123	0	0.009	220
Al	0.220	-	-	30
35Al65V	0.370	0.027	0.180	60
GA Ti-6Al-4V	0.176	0.004	0.025	520

Table 1 Impurity contents and prices of the raw powders used to produce Ti-6Al-4V components in this study. (From paper: 'Technological design of Geometrically Complex Ti-6Al-4V parts by Metal Injection Molding' by Shulong Ye, et al. Journal of Applied Sciences, Vol. 9, No. 7, 2019, 10 pp.)

Ti-6Al-4V is one of the most important and widely-used titanium alloys. Its high strength-to-weight ratio and excellent corrosion resistance provide advantages in application areas such as the aerospace, medical, marine, chemical and electronics industries. Most conventionally produced Ti-6Al-4V alloy components require significant amounts of machining and, because of the alloy's relatively poor machinability (turning, milling, drilling, reaming, etc.), the high costs involved can often limit its applications especially in complex-shaped, precision components. Metal Injection Moulding has become an attractive and economical alternative manufacturing process because it can mass produce complex shaped Ti-6Al-4V parts to net or near-net shape. Much of the research on MIM of Ti-6Al-4V alloys has been done using ultrafine gas atomised prealloyed powder and there have been some Ti alloy components successfully manufactured for industrial as well as medical and aerospace applications by the MIM process. However, the high cost of prealloyed Ti-6Al-4V powder has limited its applications in some mass production markets and is seen to be a barrier to wider utilisation of MIM Ti-6Al-4V components.

Research carried out at Southern University of Science and Technology, Shenzhen, and the University of Macau, Macau, China, has sought to develop a more cost effective way to produce complex shape, high precision Ti-6Al-4V components using a lower cost blend of gas atomised Ti powder mixed with 60Al-40V powder instead of the significantly more expensive gas atomised prealloyed powder. Results of this research have been published in a paper by Shulong Ye and colleagues in the *Journal of Applied Sciences*, Vol. 9, No. 7, 2019, p. 10.

The authors used two types of Ti-6Al-4V powders in this study. One was prepared by blending commercially pure (CP) Ti powder (99.8%, –325 mesh), Al powder (99.5%, –500 mesh) and 35Al65V powder (99.5%, –325 mesh), and this was designated as powder 'B'. A gas atomised (GA) Ti-6Al-4V prealloyed powder (99.8%, – 325 mesh) designated as powder 'P' was included for comparison purposes. The Ti, Al, and GA Ti-6Al-4V powders used in this study are spherical whilst the 35Al65V powder has an irregular shape. However, the major fraction of the blended powder in the MIM feedstock is spherical, ensuring good mouldability. Additionally, the smaller Al particles used in the blend effectively decrease the distance of diffusion, which is beneficial to achieve a uniform structure in the 'B' samples. The authors used a simple calculation to indicate that, in the fabrication of Ti6Al4V alloy components, the cost of the raw materials can be reduced by ~60% by replacing the prealloyed powder with the blended powder. Table 1 shows the impurity contents and the prices of the powders used in this study.

Feedstocks were prepared by mixing the starting powders with binders in a Z-blade kneader at 190°C with a powder loading of 60 vol.%. The 'B' powder was kneaded with binder consisting of polyformaldehyde

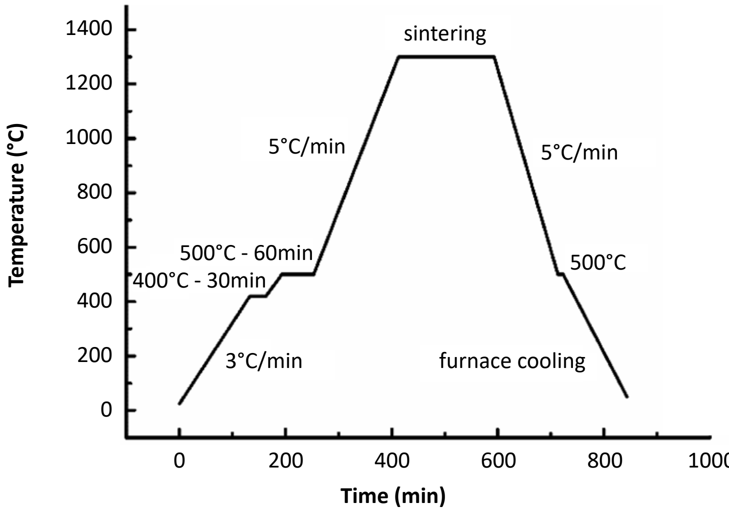


Fig. 1 Thermal debinding and sintering cycle used to produce MIM Ti-6Al-4V alloy. (From paper: 'Technological design of Geometrically Complex Ti-6Al-4V parts by Metal Injection Molding' by Shulong Ye, et al. Journal of Applied Sciences, Vol. 9, No. 7, 2019, p.10)

Specimens	O (wt.%)	C (wt.%)	N (wt.%)	Density (g/cm³)	Yield Stress (MPa)	UTS (MPa)	Elongation (%)
B-1200°C-180 min	0.318	0.071	0.028	4.26	810	927	4.6
B-1300°C-120 min	0.326	0.077	0.031	4.26	790	900	3.9
P-1200°C-180 min	0.250	0.076	0.034	4.26	818	928	5.2
P-1300°C-120 min	0.312	0.070	0.034	4.28	800	913	5.2

Table 2 Impurity content, density, and mechanical properties of the sintered MIM Ti-6Al-4V specimens. (From paper: 'Technological design of Geometrically Complex Ti-6Al-4V parts by Metal Injection Molding' by Shulong Ye, et al. Journal of Applied Sciences, Vol. 9, No. 7, 2019, p.10)

(POM), stearic acid (SA), paraffin wax (PW), ethylene vinyl acetate (EVA) and polyethylene (PE) for 60 min to achieve a homogeneous feedstock. The 'P' powder was kneaded with the same binder for 30 min. The feedstocks were injection moulded to produce 'dog-bone' tensile test bars with a nominal length of 90 mm and a gauge diameter of 5 mm. Debinding of the green bars was done by first removing most of the polyformaldehyde in a catalytic debinding furnace at 120°C for 240 min using a nitric acid vapour flow of ~2 g/min. Thermal debinding for final removal of the remaining binders and subsequent sintering were carried out in a single-step using a MIM furnace. Sintering was conducted under flowing argon at 1200°C for 180 min and 1300°C for 120 min, respectively, followed by controlled furnace cooling (Fig. 1).

The 'B' samples sintered at 1200°C for 180 min have a density of 4.26 g/cm³, yield strength of 810 MPa, ultimate tensile strength (UTS) of 927 MPa, and elongation of 4.6%. For comparison, the 'P' samples sintered at 1200°C for 180 min also have a density of 4.26 g/cm³, yield strength of 818 MPa, UTS of 928 MPa, and elongation of 5.2%. The oxygen content increases to 0.3 wt.% when samples are sintered at 1300°C while the carbon content and nitrogen content are consistently controlled to 0.07–0.08 wt.% and ~0.03 wt.%, respectively. Table 2 summarises the impurity content, density and mechanical properties of the two Ti-6Al-4V alloys processed by MIM.

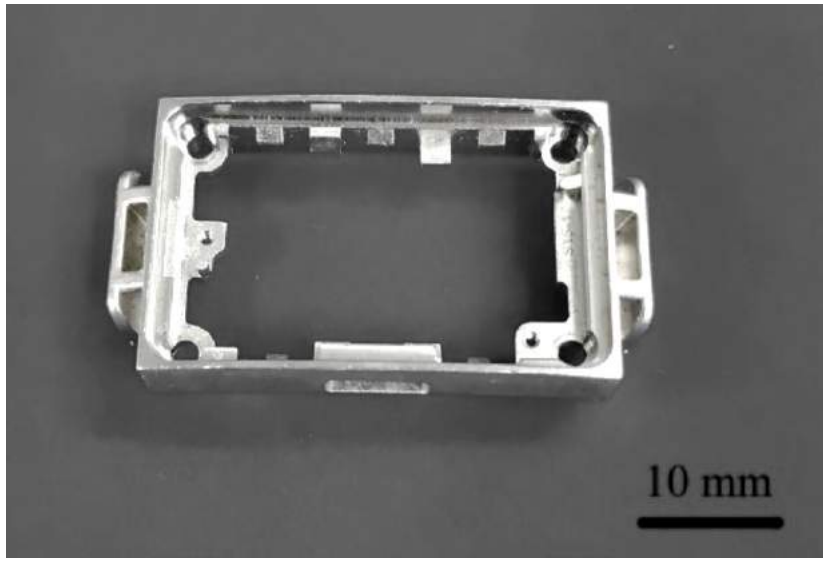


Fig. 2 Ti-6Al-4V watch case fabricated by Metal Injection Moulding from blended. (From paper: 'Technological design of Geometrically Complex Ti-6Al-4V parts by Metal Injection Molding' by Shulong Ye, et al. Journal of Applied Sciences, Vol. 9, No. 7, 2019, p.10)

The authors reported that whilst the O_2 level at 0.3 wt.% in the sintered MIM Ti6Al4V sample and also the elongation value at 4.6% do not meet the requirements of the aerospace industry standard, which requires O_2 levels not to exceed 0.2 wt.%, the material's high strength and acceptable ductility are sufficient for many engineering or appliance applications. For example, the authors used the 'B' blended powder to produce a watch case by MIM, using mould flow software to determine the optimum moulding conditions and gate positions. The sintered MIM Ti6Al4V watch case shown in Fig. 2 has a density of 4.26 g/cm³, weighs just ~6 g, and has a curved surface and complex internal structures all of which are achieved by injection moulding without any dimensional distortion or machining.

https://scialert.net/jhome.php?issn=1812-5654 ■

New developments in oxide fibre reinforced ceramics produced by PIM

In recent years Ceramic Matrix Composites (CMCs) have attracted the attention of material researchers for applications such as highly heat stressed components for combustion engines and in aero engines, not because fibre reinforcement of the ceramic enhances intrinsic strength values, but to change their brittle failure behaviour to a quasi-ductile stepwise failure by restricting crack propagation. Currently, such CMCs can be produced by infiltration but this is not considered to be an economic approach for large-scale production, and progress in adopting CMCs for highly-stressed applications has, therefore, been limited.

Researchers at the Institute for Applied Materials (IAM-WK), Karlsruhe Institute of Technology (KIT), Germany, have in recent years been investigating the potential of using Ceramic Injection Moulding to produce CMC components, and a report on some of the initial results of processing short-fibre reinforced alumina CMCs was published in *PIM International*, March 2018 (Vol. 12, No. 1, 2018, pp. 84-86). Here it was reported that the early stages of research were aimed at 1) the development of feedstocks containing a constant solid content of 50 vol.% while the powder-fibre ratio varied up to 50 vol.% fibres, 2) assessing the required injection moulding conditions, and 3) investigation of the injection moulded CMC samples in the green and sintered states. The Al_2O_3 powder used had a particle size of (D50 = 0.2 µm) and the Al_2O_3 fibres were 3.2 mm in length and 10-11 µm in diameter. The binder used (at 50 vol.% in the feedstock) was KIT's proprietary GoMikro binder system consisting of polyethylene, paraffin wax, and stearic acid. Because the Al_2O_3 fibres can break during mixing in the kneader, mixing time is less than for standard feedstock mixing in order to keep fibre length as long as possible.

In a further report presented at the 2018 PM World Congress, Beijing, China, and published in the proceedings (pp. 725-731), the KIT researchers were able to demonstrate that the final structure and porosities of alumina CMCs produced by CIM are sensitive to the amount of input fibre materials, preparation of feedstocks and the chosen injection moulds. Because the sintered porosity is fibre content and orientation dependent, the amount of fibres should be at a certain level (min. 30 vol.%). The researchers also stated that the orientation of the fibres can be controlled by the mould design, and this can be supported by the shortened feedstock preparation process in which the fibre length can be protected. Fibre orientation in the CIM samples was found to clearly affect material properties such as density and bending strength.

The most recent results of the CMC research project were presented at the Euro PM2019 International Congress, Maastricht, the Netherlands, October 13-16, and Volker Piotter and colleagues at the Institute for Applied Materials, showed that whilst the effect of fibre filling on the feedstock viscosity was hardly detectable, the green injected moulded parts clearly had sections of higher and lower fibre orientation. A higher degree of fibre orientation was found to lead to a higher density as the fibres could be stacked more closely, and this was verified by density measurements after debinding in hexane for 24-48 h and sintering (1250°C, 2 h).

The researchers therefore used a new approach to investigate shear-induced fibre orientation in the injection moulding of the CMC feedstock. This involved developing injection processes with definite flow conditions, and an experimental tool was designed, constructed, and mounted on one of KIT's Powder Injection Moulding machines. The

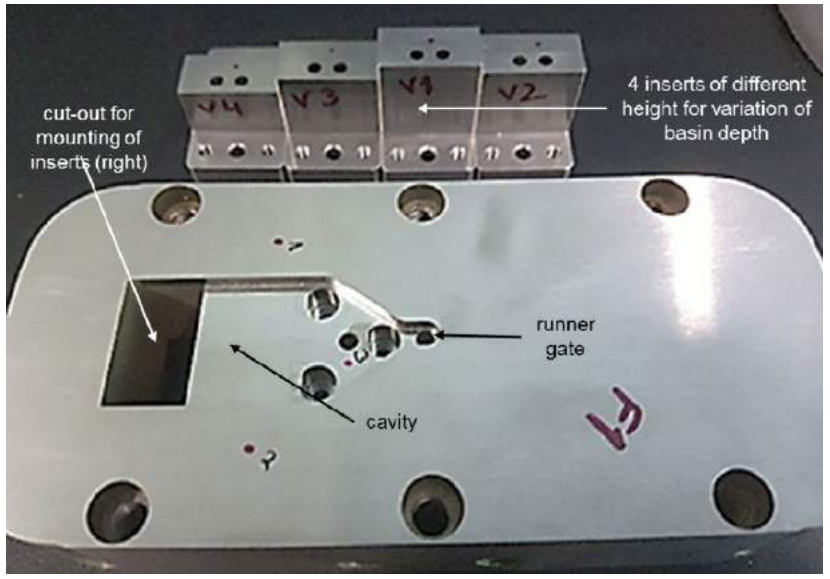


Fig. 1 Top view on the parting plane (ejector side) of the new experimental injection moulding tool to control fibre orientation in CMCs. Flow stream runs from the gate in the middle sinistrality through the cavity into the overflow basin (cut-out). Here the tool is equipped with a broad flow channel cavity instead of bending bar cavity. (From paper: 'Investigations on the processing behaviour of non-spherical particles', by V Piotter, et al. Presented at the Euro PM2019 Congress, Maastricht, October 2019)

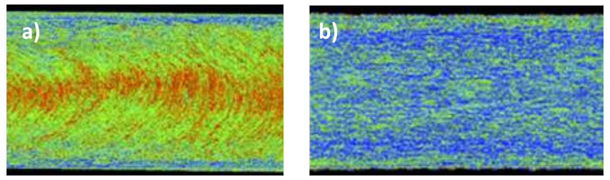


Fig. 2 Fibre orientation profiles as determined by CT. Without subsequent overflow (a) and with overflow basin (b). Flow direction from left to right. Red/green/blue = low/medium/high degree of orientation. (From paper: 'Investigations on the processing behaviour of non-spherical particles', by V Piotter, et al. Presented at the Euro PM2019 Congress, Maastricht, October 2019)

tool, shown in Fig. 1, enabled a steady flow through a specimen geometry with small (bending bar geometry, not depicted by Fig. 1) or broad width. After passing the specimen geometry the feedstock flow reached an overflow basin which could be equipped with different inserts to vary the volume (see cut out in Fig. 1). As the feedstock fills the overflow basin the fluid stream is kept constant and cools down simultaneously due to the low tool temperature. The result of this procedure is a nearly full fibre orientation through the whole cross section of the moulded specimen.

Fig. 2(a) shows the shear-induced fibre orientation profile inside the green CMC body without the overflow basin, i.e. without subsequent overflow. It can be seen that the apparent degree of fibre orientation is higher nearer the surface region than in the bulk. On the other hand, if the overflow basin was used, a nearly complete fibre orientation could be obtained throughout the whole cross section of the body, as can be seen in Fig. 2(b).

CMC specimens produced without overflow reached theoretical densities of approx. 51%, whereas the higher-oriented specimen reached values of approx. 64%. Bending tests showed an influence of the sintering parameters as well. If sintering took place at 1100°C for 30 min a maximum bending strength of only 25 MPa was achieved. Once the sintering parameters were increased to 1250°C for 2 h the bending strength increased to approx. 44 MPa. However, such values are still quite low compared to the pure alumina material (up to 300 MPa) and can be attributed to the still relatively high porosity of more than 30% in the sintered powder injection moulded CMC.

However, the authors emphasised that the intention of fibre filling is not to increase the infinite strength values of the alumina CMC but rather to improve the material's breaking resistance capabilities. In this respect, all specimens with high fibre orientation showed increased elongation before brittle fracture, thus obtaining a certain strain reserve. Nevertheless, absolute strength values of the PIM alumina CMCs are still too low, mainly as a result of the high porosity in the sintered material and the researchers still have the intention to solve this issue.

www.kit.edu

Improved properties of AZ81 magnesium alloy produced by MIM

In the June 2018 issue of *Powder Injection Moulding International* (Vol. 12, No. 2, pp. 41-42) we reported on work at the Helmholtz-Zentrum Geesthacht, Germany, on the potential use of Metal Injection Moulding to produce complex-shaped magnesium alloy components for technical applications. One alloy was based on gas atomised Mg-2.6Nd-1.3Gd-0.5Zr-0.3Zn powder designated EZK400 and this was processed by pressing and sintering. The second was a Mg-8Al-1Zn alloy referred to as AZ81 which was processed by MIM. The initial results of mechanical testing were given for both alloys. However, the authors concluded that in order to implement the use of the MIM process to produce Mg alloy AZ81 alloy components, an improvement in strength values was required.

A more recent study on how to improve the mechanical properties of MIM Mg alloy AZ81 was undertaken by Johannes G Schaper and colleagues, also at the Helmholtz-Zentrum Geesthacht, and the results have been published in the *Journal of Materials Processing Technology* (Vol. 267, May 2019, pp. 241-246). In this work the researchers focused on how the sintering kinetics of complex Mg alloys such as AZ81 could be improved in order to achieve higher mechanical properties. The composition of the spherical AZ81 powder used was 7.7 wt.% Al, 0.6 wt.% Zn, 0.3 wt.% Mn, balance Mg, with the alloy having a theoretical density of 4.81 g/cm^3. MIM feedstock was prepared by mixing the AZ81 powder with a 35 wt.% polypropylene, 60 wt.% wax, 5 wt.% stearic acid binder system. Powder loading in the feedstock was 64 vol.%. Injection moulded dog bone shaped tensile test specimens were produced according to ISO 2740-B (Fig. 1).

Optimisation of the MIM processing steps such as debinding and sintering had already been investigated previously by the researchers with the MIM AZ81 test bars first solvent debound at 40°C in hexane. This was followed by thermal debinding and sintering in a hot wall retort furnace. Thermal debinding was performed by initially increasing the temperature from 350°C to 460°C with a heating rate of 0.5 K min^{-1} with an alternating pressure between 5 and 30 mbar at an Ar+5 vol.% H_2 purge gas flow of 0.5 l min^{-1}, followed by vacuum up to 500°C. At 500°C pure Ar up to a pressure of 30 mbar was introduced whilst increasing the sintering temperature to 605°C with a heating rate of 2 K min^{-1}. The sintering temperature was maintained for

Fig. 1 Mg AZ81 dog bone shape tensile test specimen according to ISO 2740-B; (top) green part and (bottom) sintered part. (From paper: 'Powder injection moulding and heat treatment of AZ81 Mg Alloy', J G Schaper, et al. Journal of Materials Processing Technology Vol. 267, May 2019, pp. 241-246)

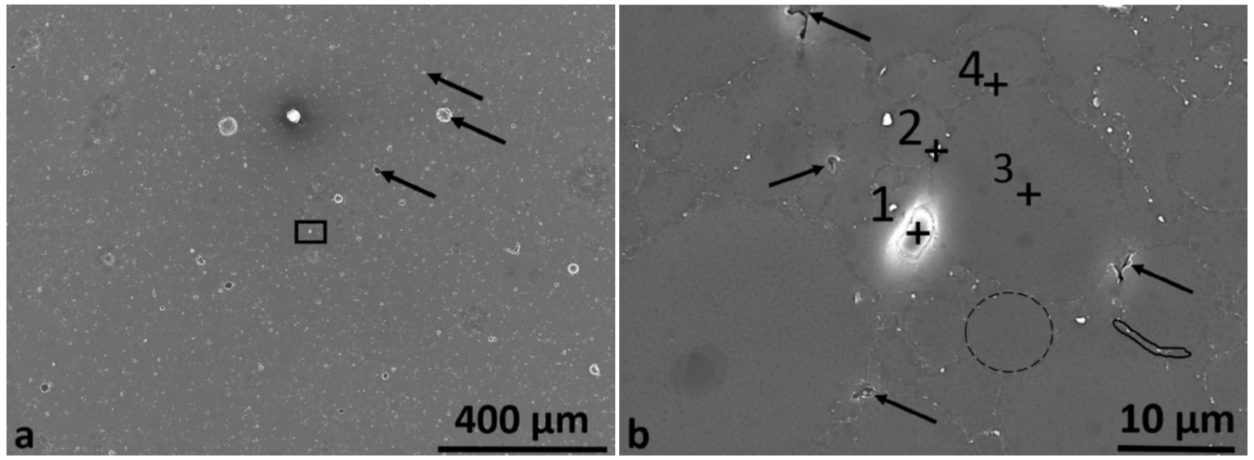


Fig. 2 (a) SEM micrograph of as-MIM AZ81 alloy (b) higher magnification of black rectangle from (a). (From paper: 'Powder injection moulding and heat treatment of AZ81 Mg Alloy', J G Schaper, et al. Journal of Materials Processing Technology Vol. 267, May 2019, pp. 241-246)

Condition	Yield Strength (±SD) [MPa]	Ultimate Tensile Strength (±SD) [MPa]	Elongation at Fracture (±SD)
AZ81 MIM	121 (±1)	257 (±5)	7% (±1%)
AZ81 MIM+T4	113 (±2)	226 (±5)	5% (±1%)
AZ81A-T4 sand cast [a]	80 - 100	250-290	11% - 14%
AZ81A-T4 permanent mold[a]	75 - 95	235-260	7% - 13%
(a) taken from (Avedesian and Baker, 1999)			

Table 1 Mechanical properties of AZ81 MIM and MIM+T4 heat treatment. (From paper: 'Powder injection moulding and heat treatment of AZ81 Mg Alloy', J G Schaper, et al. Journal of Materials Processing Technology Vol. 267, May 2019, pp. 241-246)

4 h followed by furnace cooling. The residual porosity of just 1.3% in the sintered AZ81 was determined using image analysing software. This relatively short sintering time compares with 64 hours at 637°C required for MIM Mg and Mg-0.9Ca alloy which had a residual porosity of around 3%.

The high sintered density in the MIM AZ81 alloy was said to be due to the higher amount of liquid phase fraction present during sintering (89.5 wt.%) compared with Mg-0.9Ca at 37.3 wt.%. The authors stated that if the amount of liquid phase is increased more powder is surrounded by this liquid phase, which increases the diffusion process due to the greater contact between the powders. This leads to a sintering process without necking in the first stage of sintering. They hypothesised that the wetting angle of AZ81 liquid phase is lower compared to that of Mg-0.9Ca, resulting in higher acceptable liquid phase amount without exuding liquid phase from the parts. However, to prove this hypothesis more investigations such as contact angle measurements, are needed.

Fig. 2 shows the microstructure of the MIM AZ81 samples and the residual porosity can be clearly identified (black arrows). Some MIM AZ81 samples were given a T4 heat treatment (420°C tor 10 h) which leads to a coarser grain size in the MIM+T4 AZ81 alloy compared with the as-MIM AZ81 samples as can be seen in Fig. 3. The coarser grains in the heat treated T4 samples was said to contribute to the overall decrease in mechanical properties of the MIM AZ81 alloy, as can be seen in Table 1.

The mechanical properties of as-MIM AZ81 includes a yield strength of approx 120 MPa, an ultimate tensile strength (UTS) of approx. 255 MPa and an elongation at fracture of 7%. UTS as well as elongation match those of conventionally cast AZ81 material in T4 condition. The higher yield strength might be due to a strengthening effect of the oxide and Al-rich phase precipitations at the former powder particle boundaries.

However, as stated above applying T4 heat treatment did not improve the mechanical properties of the MIM material; rather it decreased them as a result of a grain growth effect that could be proven using EBSD measurements (Fig. 3). The researchers also carried out an in-depth literature review which showed that this was the first time that grain growth has been observed for Mg-MIM material. Adjusting the temperature and time for the T4 or ageing heat treatment could be an option to improve mechanical properties further compared to the as-MIM material. They also concluded that the research carried out shows that it is possible to use MIM as an economical production route for complex shaped Mg components in high quantities with as-sintered properties that match those of cast + T4 heat treated AZ81 alloy.

www.journals.elsevier.com/journal-of-materials-processing-technology

www.hzg.de

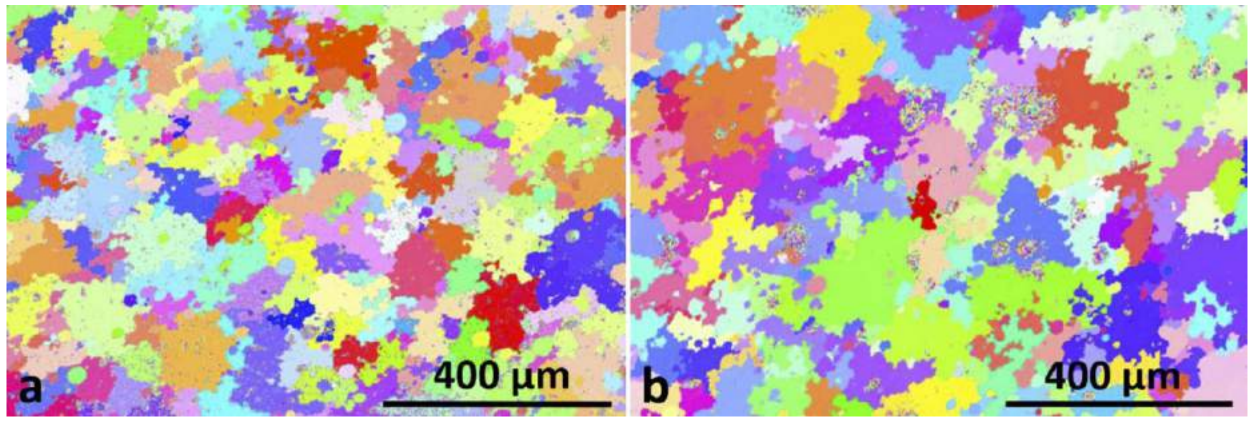


Fig. 3 (a) EBSD AZ81 MIM grain size 45 µm, (b) EBSD AZ81 +T4 grain size 62 µm. (From paper: 'Powder injection moulding and heat treatment of AZ81 Mg Alloy', J G Schaper, et al. Journal of Materials Processing Technology Vol. 267, May 2019, pp. 241-246)

Study underlines positive nanoparticle effect on injection moulding of bimodal powder feedstock

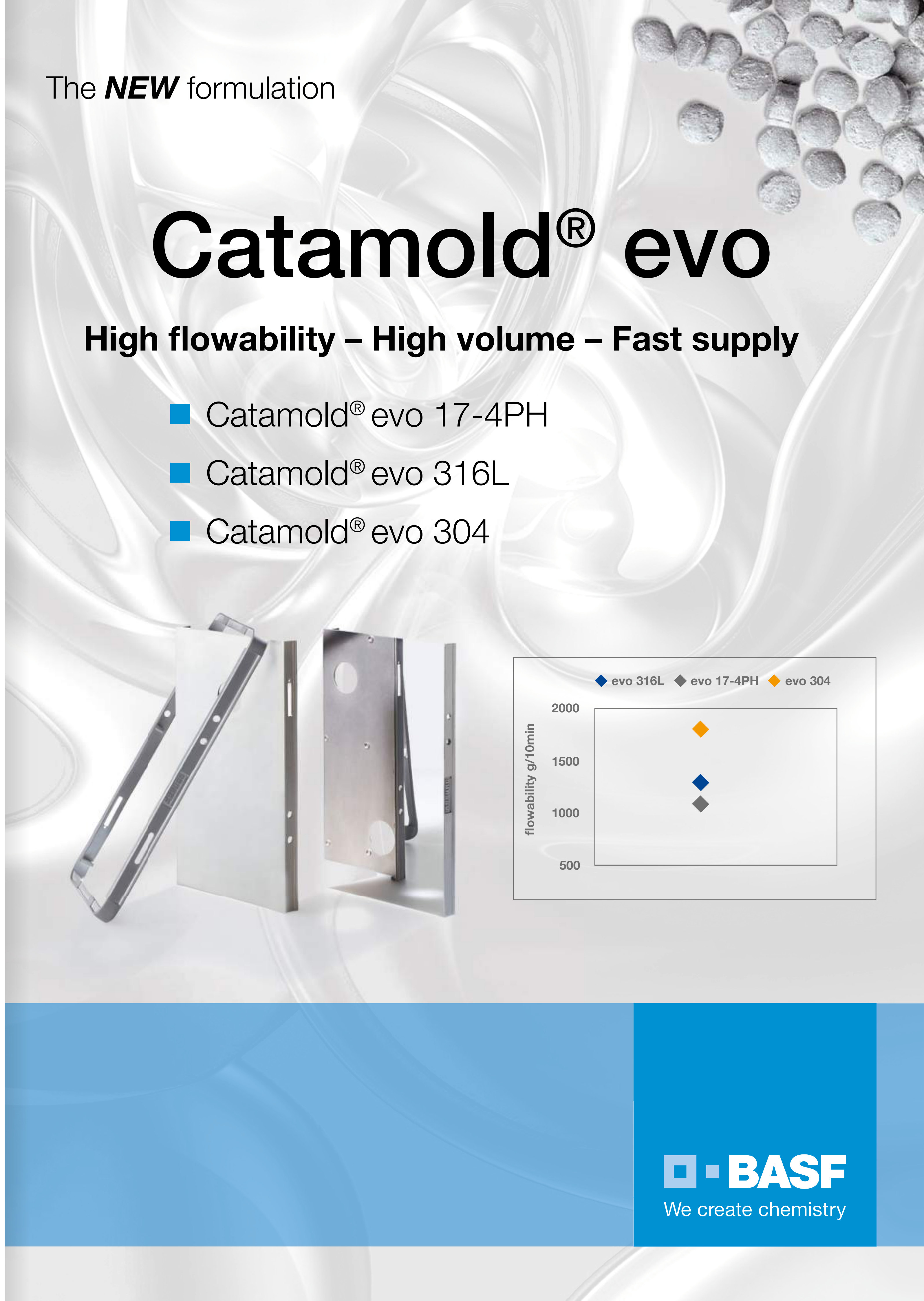
The combination of nano and micro powders to produce bimodal feedstock is considered to be a cost-efficient alternative to pure nano powder for feedstock needed to produce powder injection moulded parts with micro features and with good mechanical properties. A number of research groups have studied the use of nano powders and bimodal nano/micro particle combinations; however, little has been done to analyse and understand the rheological parameters for such bimodal feedstocks.

Researchers at the Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH), Korea, have been examining the nanoparticle effects on rheological properties of four bimodal feedstocks containing nano- and micro-particles. The feedstocks were prepared with the nanoparticle contents ranging from 0 to 75 vol.%, and each feedstock was formulated with the optimal amounts of the powders, determined from the critical solids loadings of the powders. The latest results of the work by Joo Won Oh and colleagues at POSTECH have been published in the *Journal of Materials and Manufacturing Processes* Vol. 34, No. 4, 2019, pp. 414-421.

In previous work the researchers had studied and reported on the net effects of adding nano particles on rheological parameters of bimodal 316L stainless steel feedstock. However, as the solids loading of the feedstock was fixed at 42 vol.%, this

Powder	Micro	12:88	25:75	50:50	75:25
Nanoparticle content (vol.%)	0	12	25	50	75
Critical solids loading (vol.%)	61	61	60	59	44
Optimal solids loading (vol.%)	59	59	58	57	42

Table 1 The critical and optimal solids loadings of the micro powder and bimodal powders. (From paper: 'Comparative study of nanoparticle effects on feedstock behaviour for injection molding', by J W Oh, et al, Journal of Materials and Manufacturing Processes, Vol. 34, No. 4, 2019, pp. 414-421)



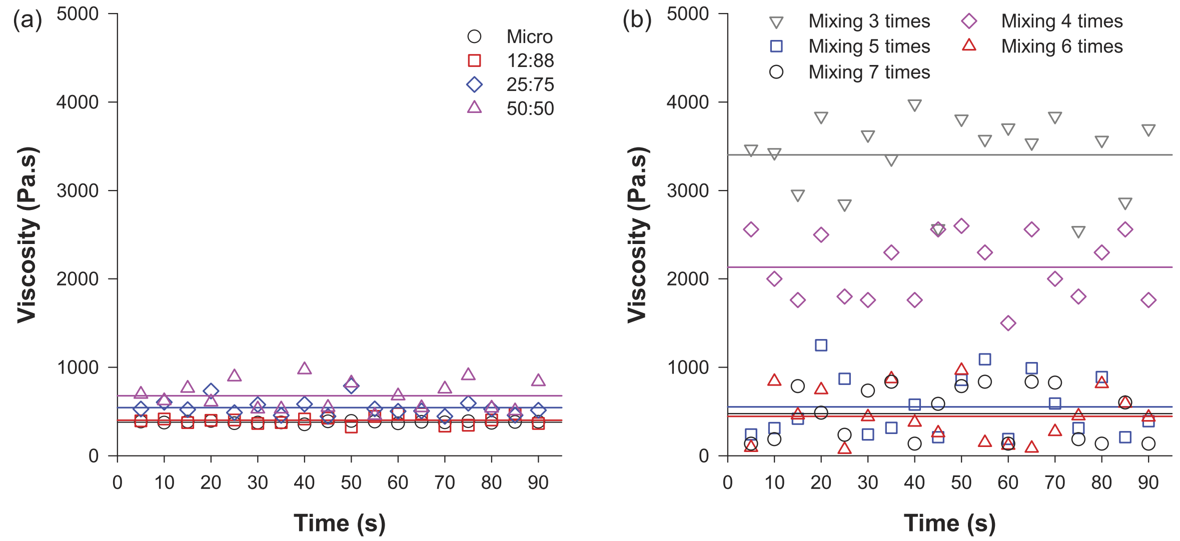


Fig. 1 Viscosity of feedstocks under a constant shear rate of 10^{s-1}: (a) four times mixed feedstocks and (b) viscosity of 75:25 bimodal feedstock with different mixing times. (From paper: 'Comparative study of nanoparticle effects on feedstock behaviour for injection molding', by J W Oh, et al, Journal of Materials and Manufacturing Processes, Vol. 34, No. 4, 2019, pp. 414-421)

was found to be too low to achieve high enough sintered density when sintered at 1350°C for 2 h, resulting in low mechanical strength of the sintered bimodal MIM parts. The researchers stated that increasing the solids loading of the bimodal feedstocks to 59 vol.% resulted in sintered density of 97% under the same sintering conditions. They therefore undertook rheological analysis of the feedstocks with increased solids loadings, including the most desirable nanoparticle content for injection moulding of the bimodal feedstocks, using feedstock viscosity measurements and the mouldability index.

The researchers used commercially available 100 nm and 4 µm 316L stainless steel powders as starting materials. The nanopowder and the micropowder were mixed in a turbula mixer with nanoparticles in the bimodal powders determined as 12, 25, 50, and 75 vol.%, and these were mixed using a binder system which contained: paraffin wax (PW), stearic acid (SA), polyethylene (PE), and polypropylene (PP). Feedstock fabrication was carried out at 160°C and 30 rpm with a twin screw mixer, and included a pure micro powder plus binder for comparison with the four nano-bimodal grades.

Determination of the solids loading is a critical step in the PIM process because it primarily affects the feedstock characteristics and quality of PIM parts. A low solids loading causes poor mechanical properties with low-density samples, and a feedstock with a higher solids loading

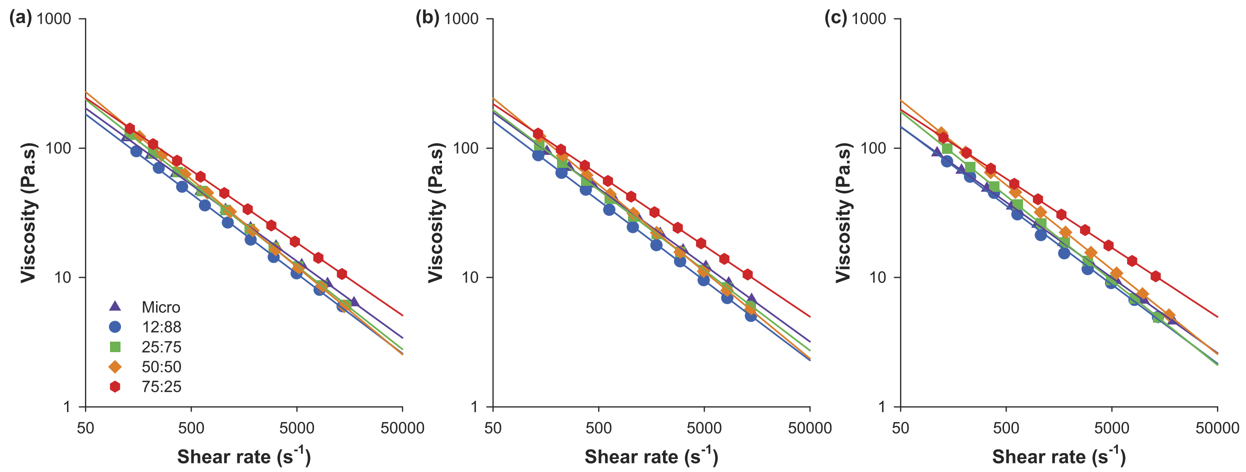


Fig. 2 Viscosity of the PIM feedstocks at (a) 150°C, (b) 160°C, and (c) 170°C. (From paper: 'Comparative study of nanoparticle effects on feedstock behaviour for injection molding', by J W Oh, et al, Journal of Materials and Manufacturing Processes, Vol. 34, No. 4, 2019, pp. 414-421)

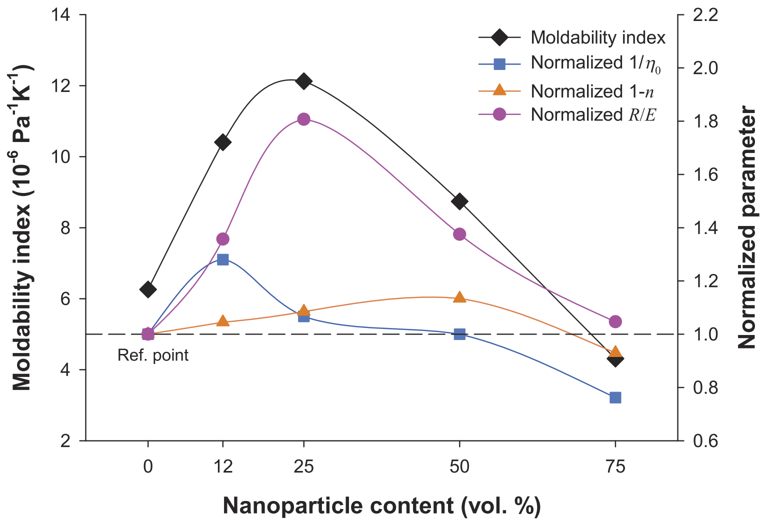


Fig. 3 Mouldability index with different nanoparticle contents. (From paper: 'Comparative study of nanoparticle effects on feedstock behaviour for injection molding', by J W Oh, et al, Journal of Materials and Manufacturing Processes, Vol. 34, No. 4, 2019, pp. 414-421)

is therefore desirable. However, too high a value means a lack of binders which could reduce the feedstock homogeneity and rapidly raise the bimodal feedstock viscosity. The researchers stated that the optimal solids loadings of each powder were determined from the critical solids loading, which is a condition where particles are tightly packed whilst binders fill the empty space between the particles. When the amount of powder in a feedstock exceeds the critical level, an abrupt increase in mixing torque is observed due to rapid viscosity change, and the researchers therefore examined solids loading as a dependency on mixing torques in order to obtain the critical value for subsequent processing. The critical and optimal solids loading values of each powder are listed in Table 1. The authors reported that whilst nanoparticles in the bimodal powders reduced the critical solids loading of the powders, the bimodal packing effect offsets the reduction, so relatively high critical solids loading values were observed up to 50% nano-bimodal powder.

To provide the desirable flowability for the feedstocks, it was determined that 2% lower solids loading than the critical level provided the optimal solids loading. The nanoparticles were also found to decrease the feedstock homogeneity because of their large surface area and agglomeration of the nanoparticles. However, as shown in Fig. 1 (a) feedstocks mixed four times had low viscosity and small viscosity fluctuations which implies that the feedstocks were sufficiently homogeneous to be injected. The viscosity did not show any dependency on the nanoparticle content due to different solids loadings of each feedstock. The authors reported that whereas the 75:25 bimodal feedstock in Fig. 1 (b) still showed high viscosity and viscosity fluctuation after mixing four times, both values decreased continuously when mixing six times to maximum homogeneity. Fig. 2 shows the viscosity of the feedstocks at different temperatures.

The flow behaviour index, which represents the sensitivity of viscosity vs shear rate, and flow activation energy where the sensitivity of viscosity depends on temperature, were obtained with the Arrhenius and power-law models using a moulding temperature of 160°C and shear rate of 1000 s^{-1}. The authors stated that both flow behaviour index and flow activation energy tended to be reduced by the nanoparticles. As a result, most bimodal feedstocks were more desirable for injection moulding than standard micro powder feedstock except for the 75:25 bimodal feedstock.

However, the optimal nanoparticle contents for each parameter were not consistent, and the authors introduced the mouldability index to determine the optimal nanoparticle content. Fig. 3 shows the mouldability index of the bimodal feedstocks with different nanoparticle contents. The results indicated 25 vol.% was the most desirable content of the nanoparticles for the Powder Injection Moulding process.

www.postech.ac.kr | www.tandfonline.com/loi/lmmp20

Mimecrisa: Pushing the limits of Metal Injection Moulding technology

Mimecrisa, the Metal Injection Moulding business of Spain's Ecrimesa Group, based in the northern city of Santander, is one of Europe's leading MIM manufacturers, with more than twenty-five years' experience in the technology. The company, which was the world's first MIM manufacturer to install a continuous sintering furnace for MIM part production, continues to go from strength-to-strength, with a reputation in particular for the production of parts that push the size limits of the technology. Georg Schlieper recently visited the company on behalf of *PIM International* and reports on the history and current status of the company.

Founded in 1964 in Santander, the capital of the Autonomous Province of Cantabria on Spain's north coast, Ecrimesa is a family-owned group of metalworking companies. The name Ecrimesa is a compound of the Spanish Electro Crisol Metal S.A., translating as 'Electric Metal Melting Crucible'. The company was originally established for the production of steel and aluminium investment castings, but, while Investment Casting (IC) remains the main pillar of Ecrimesa's business, its Metal Injection Moulding business is currently growing faster than IC and is close to taking the lead.

In the late 1980s, Ecrimesa's management recognised the potential of the emerging MIM process as an addition to its Investment Casting business that could give it access to the market for smaller precision parts. The company was one of the first IC manufacturers to invest in MIM and the early 1990s saw a phase of intensive research and development activities as well as the installation of the first manufacturing facilities for MIM parts.

At that time, Germany's BASF had recently introduced its Catamold® feedstock and catalytic debinding process to the MIM industry and soon became the most important and largest feedstock supplier in the world; Ecrimesa relied on BASF feedstocks from the start. In 1994, it purchased the first continuous furnace designed specifically for MIM parts from Cremer Thermoprozessanlagen GmbH. The design of this furnace was based on Cremer's walking-beam technology, which had been successfully used in the high-temperature sintering of

Fig. 1 Mimecrisa has been a leader in the development of the MIM industry in Europe for more than twenty-five years

Fig. 2 One of three MIM-Master continuous debinding and sintering furnaces operating at Mimecrisa

press and sinter PM parts for many years. Cremer installed a catalytic debinding zone parallel to the walking-beam furnace, and the wax burn-off zone of the conventional walking-beam furnace was replaced with a new unit for the thermal decomposition of the backbone binder with a pusher-type transport mechanism.

Despite many similarities in the high-temperature sintering of axially-pressed PM parts and MIM parts, there were some significant differences that had to be considered when introducing such a novel sintering furnace. The biggest challenge proved to be the transition from the thermal debinding zone to the sintering zone; when the backbone binder has been removed, MIM components, and stainless steel parts made from pre-alloyed gas or water atomised powders in particular, are extremely fragile and may collapse at the slightest shock. Because the vibrations produced by the pusher mechanism were too intense and could damage the furnace load, Cremer developed a novel solution specifically for MIM parts with an improved walking-beam mechanism for both the thermal debinding of the backbone binder and sintering of the part.

To minimise the risk of damage to the fragile MIM parts made from pre-alloyed stainless steel powders when burning out the residual binder, BASF was asked to develop feedstocks based on master alloy powders. Ecrimesa was grateful for the professional support of BASF's technical staff, who came directly from the R&D team that had developed the catalytic debinding process. Ecrimesa and Cremer cooperated closely to solve many of the initial teething problems that the continuous processing of MIM parts presented. Based on these improvements, Cremer developed a whole family of continuous debinding and sintering furnaces under the name of MIM-Master. Today, a large fleet of MIM-Master furnaces of various capacities is operated around the world for high-volume MIM production.

By 1997, Ecrimesa's MIM operation had grown to such an extent that the company's management took the decision to install a new, bigger MIM-Master furnace in a larger location closer to Ecrimesa's headquarters. This furnace had a walking-beam transport through the thermal debinding and sintering zones and was equipped with more heating elements in order to allow more complex sintering profiles that are closer to those found in batch process. Further, an independent company under the name Mimecrisa was established. The new company took over the MIM production facility, along with the workforce that had been trained to operate it, while sales and marketing, administration and tooling operations remained within Ecrimesa.

Today, the Ecrimesa Group is made up of three companies that are all located in adjacent buildings in Santander; the Investment Casting company Ecrimesa, the MIM manufacturer Mimecrisa and the machining company Mecansa. The companies work closely together, benefitting from one another's capabilities and expertise. For example, the tool shop at Ecrimesa provides toolmaking and tool maintenance services to Mimecrisa, along with access to its metallurgical and measuring labs; Mecansa also carries out finish machining operations, mainly for Ecrimesa but also for Mimecrisa if required, and both Mimecrisa and Mecansa make use of Ecrimesa's heat treatment capabilities.

Manuel Caballero, Technical Director of both Ecrimesa and Mimecrisa, is the driving force behind Mimecrisa's success. Having graduated from Valladolid University in 1986 with a master's degree in Chemical Engineering, he was appointed Head of Ecrimesa's Metallurgical Laboratory in 1988. Since the start of MIM development at Ecrimesa in 1991, he has been responsible for the development and installation of all the company's MIM production capacity and became Head of R&D in 1994, with responsibility for the transition to mass production.

Since 2007, Caballero has had full responsibility for all technical matters relating to both Investment Casting and MIM, including production planning, research & development, processing and the metallurgical laboratories. In addition, he has management responsibilities in organisational planning and leading new teams in a number of departments. Additionally, he represents Ecrimesa and Mimecrisa at international conferences and seminars, actively promoting MIM and IC technology.

Fig. 3 Two Elnik Systems batch debinding and sintering furnaces at Mimecrisa

Strategic objectives

According to Caballero, the synergies made possible by a common sales organisation and the availability of IC, MIM and a plant for machining operations give the Ecrimesa Group a strong position in various markets for finished components. With a European network of agents, the group is able to respond to the needs of its customers across the continent. Its engineers strive for the best solution for each customer request and choose the best manufacturing route both technically and economically, either through MIM, IC or machining. "As a rule of thumb," Caballero stated, "smaller parts are usually better suited for MIM and, for larger ones, investment casting plus machining is usually the best technology."

The group's management pursues a policy of total customer satisfaction through diligent service and the timely delivery of high-quality products. Continuous improvement initiatives for product quality and productivity are implemented and the staff are encouraged to improve their skills and increase their awareness of how to improve the quality of their work on an ongoing basis. Ecrimesa Group's quality and environmental management system is certified according to IATF 16949 (automotive), ISO 14001 (environmental) and EN 9100 (aerospace and defence).

Each year, a substantial portion of revenue is re-invested in machinery and equipment in order to modernise production and increase productivity.

MIM production at Mimecrisa

Mimecrisa almost exclusively uses commercially-available feedstocks designed for catalytic debinding. This avoids the need to invest in and maintain equipment for feedstock preparation, along with all of the specific knowledge and expertise that goes with this. All incoming feedstock deliveries are, of course, checked for compliance with specifications in the company's materials laboratory. Chemical composition is analysed, and standardised coin-shaped samples are used to determine the shrinkage factor. Differential thermal analysis equipment is used to analyse binder decomposition rates and the amount of binder in the feedstock.

Production floorspace at Mimecrisa is approximately 6000 m^2. A workforce of around fifty employees operates the twelve Arburg GmbH & Co KG injection moulding machines, three continuous MIM-Master lines (Fig. 2) and two batch furnaces from Elnik Systems (Fig. 3). The injection moulding machines, originally specified with hydraulic clamping

Fig. 4 Mimecrisa's injection moulding capability is in the process of being upgraded to the latest all-electric systems

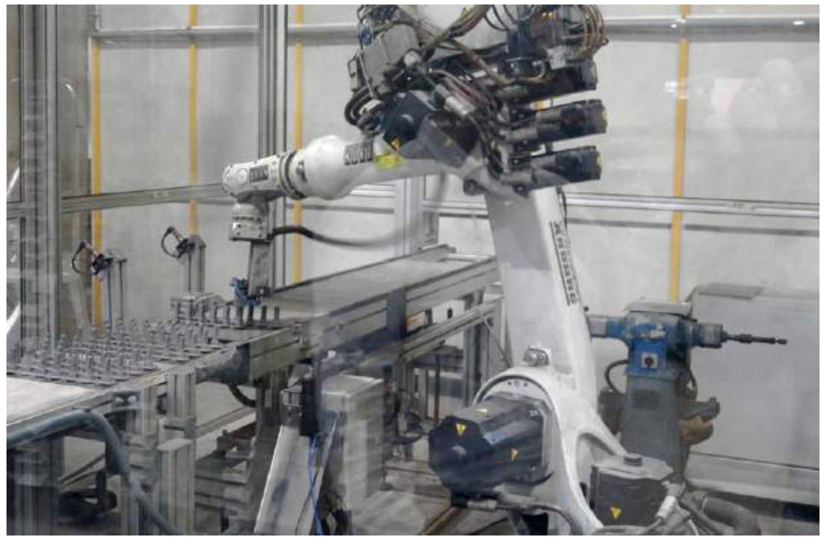


Fig. 5 A robotic arm placing green MIM parts on trays prior to debinding and sintering

systems, are gradually being replaced by fully electric machines (Fig. 4). Injection moulding tooling is supplied in part by external suppliers, and in part by Ecrimesa's in-house tool shop. Tool maintenance, cleaning, repair and modifications are managed internally.

All injection moulding machines are equipped with pick-and-place systems, one with a robotic arm (Fig. 5). Sprues and runners are recycled in a proprietary process. Green parts are placed on trays that fit into sinter boxes that are specifically designed for MIM-Master furnaces (Fig. 6). In this way, green parts do not have to be handled until they exit the sintering furnaces. In some cases, the parts are placed on specially shaped ceramic supports, or setters, for improved dimensional stability (Fig. 7). These supports are also manufactured in-house.

In order to operate its continuous sintering furnaces economically, Mimecrisa runs them twenty-four hours a day, seven days a week, processing a number of different parts at once that can share the same specific sintering cycle. Furnaces are only stopped in order to change this sintering cycle, for example for a different material or range of parts. A number of injection moulding machines at Mimecrisa are also operated in three shifts.

Sintering conditions in Mimecrisa's continuous furnaces are suited to low-alloy steels, low-carbon FN08, low-alloy steel with elevated carbon 4605, 42CrMo4, 100Cr6, 17-4PH and 316L stainless steel.

A large proportion of Mimecrisa's products are made from heat treated steels that require a higher carbon content. The production of carbonaceous sintered steels poses a special challenge for MIM manufacturers as these materials require very precise control of the sintering atmosphere. In many cases, components made from these materials are hardened and tempered following sintering – an area in which Mimecrisa has a great deal of experience. Two carburising furnaces are available for case hardening and quench-and-temper heat treatments, with fine-tuned programs for MIM materials and small parts. The installation of a third carburising furnace is underway.

The company's original continuous MIM furnace is no longer used for sintering, but rather for heat treatment. Some secondary operations such as sizing, grinding and finish machining are either carried out in-house or subcontracted to external suppliers.

Operating its own metallurgical laboratory allows the Ecrimesa group to efficiently maintain high quality standards. The laboratory is equipped with instruments to measure the pycnometric density and melt flow index of the feedstock. All state-of-the-art instrumentation and devices for metallographic inspection, carbon analysis, hardness and micro-hardness testing, tensile testing and more are available. Special attention is given to the non-destructive testing of MIM parts. Magnetic Particle Inspection and Liquid Penetrant Testing, as well as visual inspection, are applied to detect surface cracks or defects in sintered parts, while internal defects in green parts are detected with X-ray radiographic equipment, which is also capable of computer tomography.

The laboratory also features a 3D measuring table and a laser scanner for the exact measurement of tool dimensions and complex components.

Products and markets

Traditionally, Ecrimesa and Mimecrisa have held a strong position in the market for firearms for law enforcement and the military, and today a significant proportion of European police officers carry a pistol with MIM parts made by Mimecrisa. Firearms and defence accounted for 31% of Mimecrisa's sales in 2018 (Fig. 8). In addition, Mimecrisa is present in a wide variety of other market segments for structural parts, with major applications for its products found in locks, tools, textile machines and sensor housings. Mimecrisa's customer base is primarily based in Germany, Spain, France and Italy. Between sixty and a hundred new parts are implemented each year, and this number is growing.

As previously mentioned, Ecrimesa pursues a philosophy of providing a full service to its customers, including where necessary the assembly of several components. Mimecrisa also keeps an open mind as far as production volumes are concerned. There is no fixed minimum production volume, with the decision for a specific manufacturing route taken solely on technical and economic considerations.

Although the range of materials offered by Mimecrisa is wide, a relatively large portion of its production is made from low-alloy steels such as FN08, 4605 and 42CrMo4,

Fig. 6 Sinter boxes with sintered parts leaving a continuous furnace

Fig. 7 MIM parts mounted on custom ceramic setters

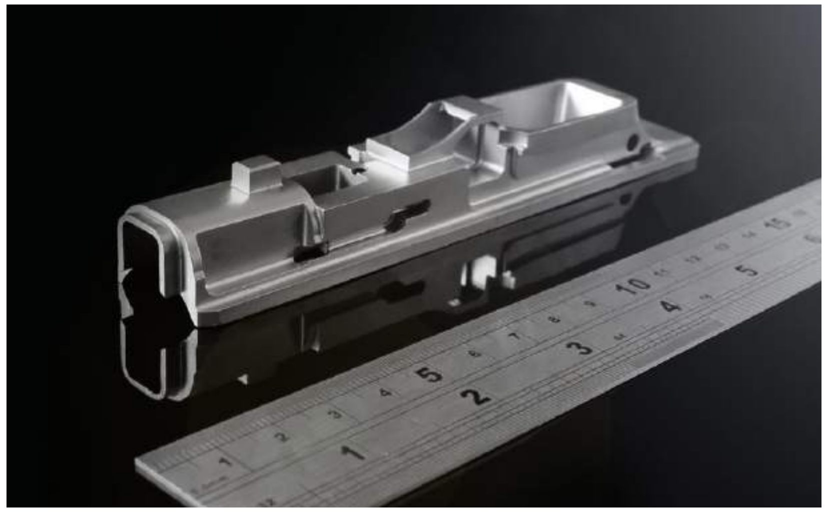


Fig. 8 This firearms component is at the largest end of MIM's size range

| contents page | news | events | advertisers' index | contact | Company visit: Mimecrisa

Fig. 9 View of the injection moulding department at Mimecrisa

reflecting the types of components required by the firearms industry. Mimecrisa's preference is for the 'master alloy' concept for alloyed steels wherever it is applicable.

The wide size range of Mimecrisa's products is well illustrated by the two applications shown in Fig. 10 in the green and as-sintered states. The largest is a firearm component made of heat treated FN08 with a weight of 254 g, while the smallest part weighs only a fraction of a gram.

Whilst door hinges are usually made from zinc alloys (Zamak) by die casting, Mimecrisa is known for manufacturing particularly high-strength door hinges by MIM (Fig. 11).

> *"Although the range of materials offered by Mimecrisa is wide, a relatively large portion of its production is made from low-alloy steels such as FN08, 4605 and 42CrMo4, reflecting the types of components required by the firearms industry."*

Innovation at Mimecrisa: Process, environment and Additive Manufacturing

Since the early days of MIM technology, Mimecrisa has been at the forefront of technical developments and innovation. Computer simulation of the injection moulding process is currently being tested intensively by the IC department to accelerate the design of tooling, to optimise mould filling and to avoid costly modifications after the tool has been finished.

Environmental protection is also a high priority. Caballero stated that Mimecrisa was the first company in the world to incorporate a system for reducing nitric oxides in the exhaust outlets of catalytic debinding equipment. The technology, which is similar to the systems used by commercial trucks, reduces the concentration of NOx in exhaust gases to as low as 400 ppm.

In 2018, Mimecrisa announced a strategic partnership with the Scaladd AM Centre, a Spanish specialist in Additive Manufacturing (AM), as well as a close cooperation with universities and technical institutes to test and develop state-of-the-art equipment and materials for Additive Manufacturing. "We believe that AM can be a complementary technology to MIM that is able to extend the range of our production towards smaller quantities and more complex geometries," stated Caballero.

"We are not interested in laser and electron beam melting processes, but rather in Binder Jetting or Fused Filament Fabrication. These processes are closer to our MIM technology and we can use our furnaces for debinding and sintering. Our immediate objective is to use AM for rapid prototyping." With its sintering and finish machining capacities, Mimecrisa seems well prepared for a future with MIM and Additive Manufacturing.

On visiting Mimecrisa, it was demonstrated to me once again how versatile the MIM industry is and what potential there is in MIM technology. Mimecrisa's openness to cooperative research and its transparency in dealing with technical innovation, exploring the opportunities and limitations of its technology, will ultimately carry the entire industry forward for the benefit of all parties involved.

Fig. 10 The smallest and largest MIM parts produced by Mimecrisa (green and sintered, with paperclip for scale)

Fig. 11 High-strength door hinges in the green and sintered states

Contact

Manuel Caballero
Technical Director
Ecrimesa
Avda de Parayas s/n
E-39011 Santander,
Spain

Tel: +34 942 334 511
mcaballero@ecrimesa.es
www.ecrimesa.es

Author

Dr Georg Schlieper
Harscheidweg 89
D-45149 Essen, Germany
Tel: +49 201 71 20 98
georg.schlieper@hotmail.de

PMTi2019: International conference on the PM and AM of titanium highlights a bright future for sinter-based technologies

The PM Titanium conference series, previously held in Brisbane, Australia (2011), Hamilton, New Zealand (2013), Lüneburg, Germany (2015) and Xi'an, China (2017), is a key international event for those involved in the powder metallurgical processing of titanium and its alloys. In September the event reached its fourth continent, North America, being held at the University of Utah, Salt Lake City. Dr Thomas Ebel reviews a selection of conference presentations that suggest that progress on the sinter-based processing of titanium and titanium alloys continues to mature, with cost reduction high on the agenda.

The fifth biennial conference on the Powder Metallurgy and Additive Manufacturing of Titanium (PMTi2019) took place from September 24–27 at the University of Utah, Salt Lake City, USA, attracting around 140 international participants. The conference was hosted by Prof Zhigang Zak Fang, a well-respected expert in titanium and sintering processes, and co-chaired by Ali Yousefiani, Boeing; James Sears, Carpenter Technology Corporation; and Francis H Sam Froes, University of Idaho. As in previous years, an international team supported the programme's development and, for 2019, the Metal Powder Industries Federation (MPIF) acted as the conference sponsor.

While the theme of the conference was the PM and AM of titanium, the number of presentations on Additive Manufacturing, mostly by Laser Powder Bed Fusion (L-PBF), was high, while the number of presentations on conventional Powder Metallurgy processes was relatively low. This is a tendency that has been observed for some years; however, it appears that the hype around Additive Manufacturing has settled down. In the AM-focused presentations, challenges such as reproducibility, distortion, porosity and process control still dominated discussions; more mature technologies, such as MIM, remain more competitive at present.

Presentations relating specifically to MIM were relatively rare at the conference, with a trend instead being visible toward 'MIM-like' AM technologies such as metal Binder Jetting (BJT) and Fused Filament Fabrication (FFF), which enable the production of single parts or small series without the need for a

Fig. 1 PMTi2019 took place in the dynamic location of Salt Lake City, Utah (Photo courtesy Garrett/Wikimedia)

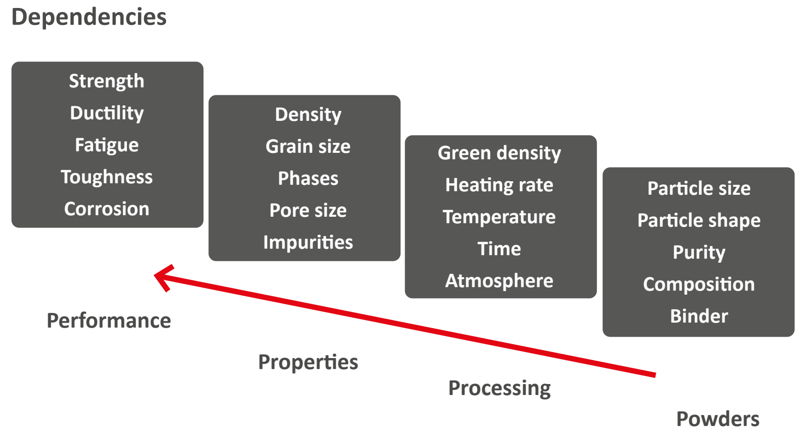


Fig. 2 Basic schematic of dependencies between sintering parameters and properties [1]

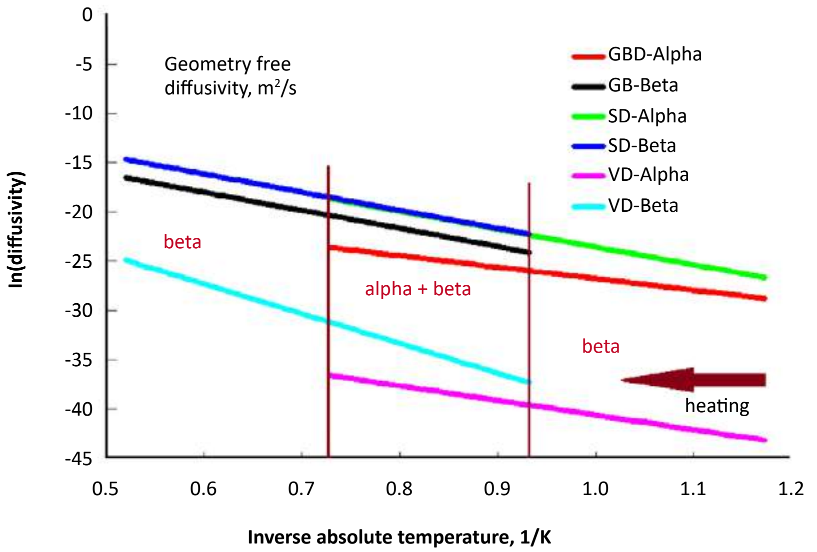


Fig. 3 Importance of different diffusion mechanisms in sintering of Ti-6Al-4V [1]

mould or tooling. Binder Jetting is, of course, being developed into a 'production technology', facilitating the manufacturing of large numbers of parts – such efforts have been widely publicised, and complete production systems including an AM machine, debinding unit and sintering furnace are now available.

Sintering and the use of feedstocks comprised of metal powder and binder are still very attractive. Many different shaping processes working with feedstock exist and some of them are actually rather cheap, such as FFF. However, not all of these technologies have been developed for the processing of titanium; this was made clear throughout the conference, as was the fact that sintering of titanium is still comparatively difficult, and specialist equipment is helpful. In one presentation, a furnace concept for the reliable sintering of titanium alloys was introduced.

Despite the dominance of presentations on L-PBF and related AM technologies, sintering was the topic of a number of presentations, starting with a keynote on the basics of sintering by Prof Randall German. In this report, a selection of these presentations are reviewed.

Basics for achieving high mechanical properties by sintering

Randall German, Professor of Engineering and former Associate Dean of Engineering Research at San Diego State University, California, USA, who is well known as one of the pioneers of both sintering and MIM, gave a comprehensive presentation on sintering with a specific focus on porosity. He pointed out that low porosity is generally the most important factor for good mechanical properties.

An evaluation of about eighty studies on the sintering of Ti-6Al-4V, using pre-alloyed as well as blended elemental powders, revealed a basic recipe to achieve high sintered density: use small powder particles, provide high green density and sinter under high vacuum (< 10^{-4} Pa). However, as Fig. 2 shows, there is a complex interaction between many processing parameters and material characteristics, particularly when sintering MIM parts. This makes it very difficult to determine optimised parameters with regard to mechanical properties. Furthermore, the use of small powder particle sizes bears the risk of introducing high oxygen content, which could significantly deteriorate ductility. Thus, proper control of impurity uptake is crucial when sintering titanium.

For Ti-6Al-4V, German emphasised the importance of the existing phases during sintering. The crystal structure of titanium changes from hexagonal (alpha phase) to cubic (beta phase) at around 880°C during heating. Thus, the diffusion speed of atoms also changes, influencing the sintering process rather strongly. Alloys such as Ti-6Al-4V provide a rather broad temperature interval where both phases exist. It is within this interval, at intermediate temperatures around 1000°C, that most of the sintering densification occurs. At higher temperatures, the beta phase alone exists, promoting final densification but also grain growth, resulting in decreasing mechanical properties. The underlying mechanism can be found in the temperature-dependent co-existence of different diffusion paths (Fig. 3, GBD: grain boundary diffusion, SD: surface diffusion, VD: volume diffusion) based on sintering theory.

This shows how important it is to know about phase diagrams and diffusivities during the development of the sintering cycle. Application of high sintering temperatures is not inherently beneficial, even if, principally, high diffusivity is connected with high temperatures. Additionally, oxygen strongly influences the phase transformation temperature. Using blended elemental powders or master alloys complicates the situation further, because chemical gradients are added, affecting the sintering behaviour, at least initially.

In the last part of his presentation, German focused on the reasons why it is almost impossible to achieve zero porosity. In 2010, Robertson and Schaffer developed the idea of a formula for the Integral Work of Sintering. Applying this formula to seventy-eight studies on sintering of Ti-6Al-4V leads to the asymptotic shape of the curve shown in Fig. 4. In addition to this basic asymptotic behaviour, there are a number of factors, such as entrapped gas, binder residues, stable oxide films and pore coarsening, preventing the pores from completely closing. In the end, German's presentation confirmed the experience that everyone working on sintering of titanium has: it is a complicated and sophisticated process to obtain the desired excellent mechanical properties. However, the presentation showed clearly the importance of understanding the physical processes. German concluded with the recipe for best practice: start with high green density, sinter with slow heating and hold for long times at low temperature in high vacuum.

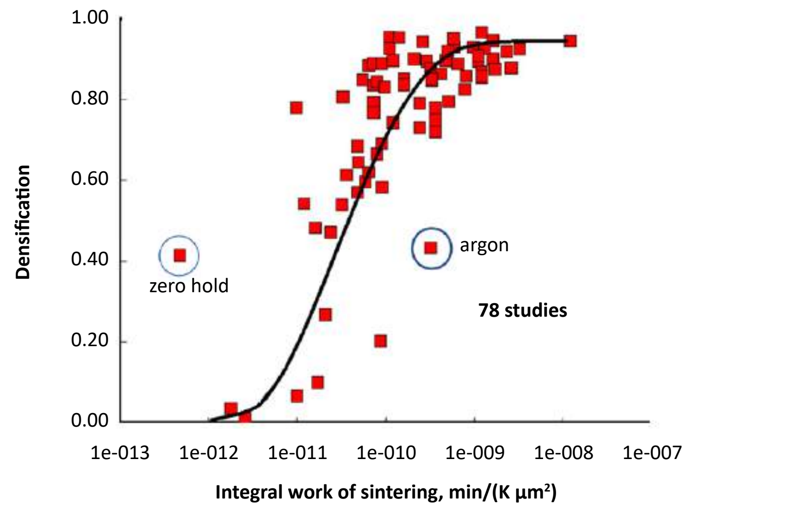


Fig. 4 Application of the formula of Integral Work of Sintering (2) on 78 studies on sintering of Ti-6Al-4V [1]

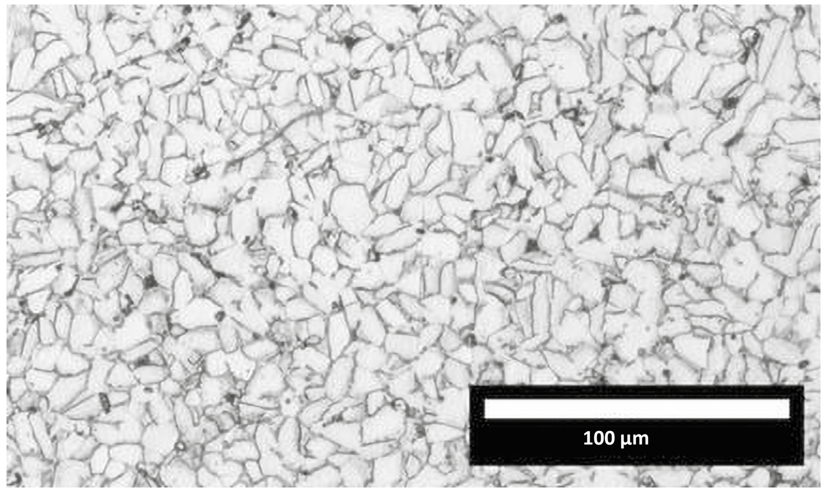


Fig. 5 Resulting microstructure in Ti-6Al-4V after sintering at low temperature [3]

Adjusting the microstructure

This general approach to sintering was confirmed in a presentation by Johannes Schaper from Element 22 GmbH, Germany. Schaper reported on work primarily conducted by his colleague, Florian Gerdts, on microstructure optimisation in MIM Ti-6Al-4V, achieved by applying a special thermal process during production. The idea was to provide small and generally globular alpha grains, similar to the typical microstructures of wrought material. This is in contrast to the standard coarse lamellar structure obtained from typical MIM processing.

For the study, fine powder with a size of < 25 µm was used and sintering was performed in the alpha and beta regime at a rather low temperature of around 1000°C. Schaper called this process Selective Bead Sintering (SBS). The resulting microstructure is shown in Fig. 5. Interestingly, a very high density of 99.8% was achieved through this method. Fatigue tests (4-point bending) revealed an endurance limit at 10^7 cycles of 640 MPa; this is at least 100 MPa higher than specimens sintered in the pure beta region. The ultimate tensile strength reaches 1000 MPa and the elongation to fracture an astonishing 20%, which is unusually high for Ti-6Al-4V.

In the second part of his presentation, Schaper showed the results of a development study of

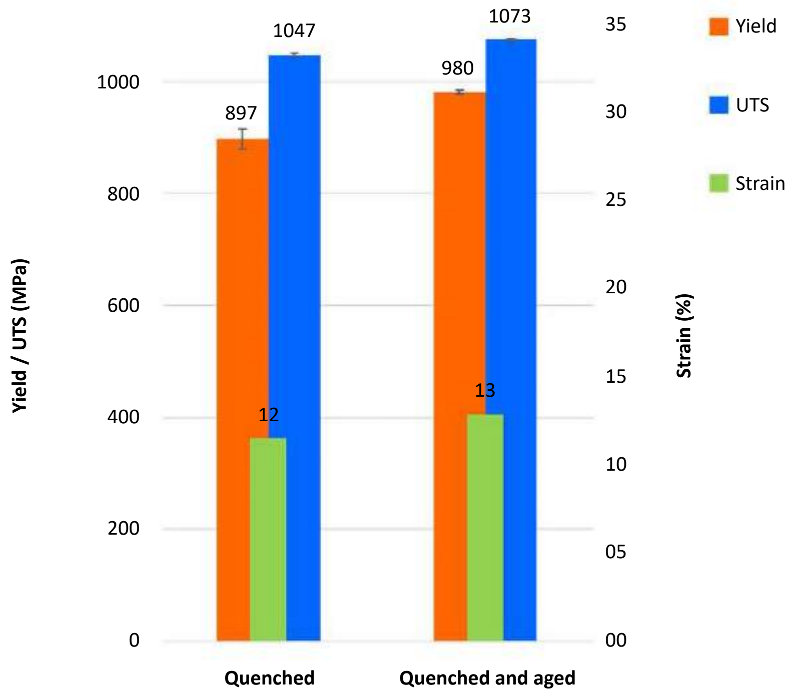


Fig. 6 Tensile properties of MIM and HIP Ti-6Al-4V after quenching from HIP temperature (lamellar microstructure) and subsequent heat treatment (bi-lamellar microstructure) [3]

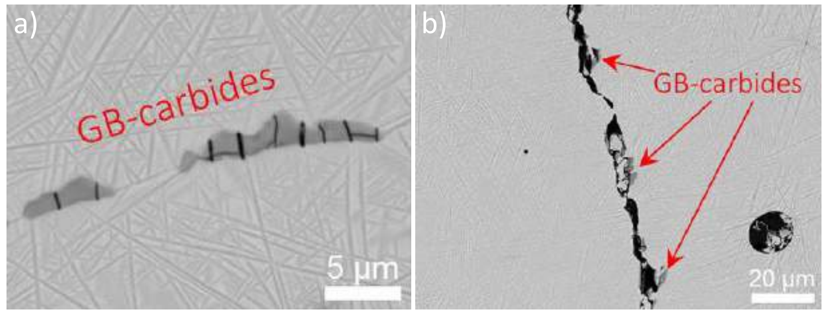


Fig. 7 Tensile loading leads to a) micro-cracks inside of the carbides and b) coalescent micro-voids along the grain boundaries [4]

an alternative route for improving the mechanical properties of MIM Ti-6Al-4V. For this, after sintering in the alpha plus beta field, a Hot Isostatic Pressing (HIP) process was applied to close the residual porosity. Because this process is usually accompanied by some grain growth, rapid quenching from the HIP temperature (955°C) was added. The quenching rate was varied between 250 and 6600 K/min in the temperature range between 880°C and 750°C. After an additional stress relief and solution treatment, a nano-sized bi-lamellar substructure of the beta-lamellae was observed. Fig. 6 compares the comparably high tensile properties of the specimens after quenching and quenching plus heat treatment. The mechanical properties achieved appear to be equivalent to wrought material.

The presentation demonstrated once more how strongly adjustment of the microstructure defines mechanical properties and that very high mechanical properties can be achieved by sintering.

Shaping of carbides

A fundamental challenge in the processing of beta-titanium alloys by MIM is the likely formation of unwanted carbides. As studies from past conferences in this series have shown, carbides are often formed along the grain boundaries due to the low solubility of carbon in the beta titanium matrix. The carbon is related to the usage of polymeric binders and studies showed that complete debinding and sintering without any uptake of carbon appears to be impossible at present.

Peng Xu, Helmholtz-Zentrum Geesthacht, Germany, presented a possible way to eliminate carbides at the grain boundaries and, instead, let them form as small spherical precipitates inside the titanium matrix. The idea is that, in the latter case, the impact of carbides on ductility will be significantly reduced.

Xu's aim was to develop a metastable beta-titanium alloy for biomedical applications, processable by MIM. The system he used was Ti-Nb-Zr plus an addition of Y. In the study, he blended Ti-42Nb (wt.%) powder with elemental Ti and Zr powders to form a Ti-20Nb-10Zr (wt.%) alloy during sintering. Processing by MIM led to the expected carbide formation at the grain boundaries. Xu showed that actual micro-cracks occur during tensile loading (Fig. 7a) and coalescent microvoids (Fig. 7b) form small cracks, which probably lead to the premature fracture of specimens.

Xu suggested the combination of a novel sintering cycle with an oxygen getter achieved "low-temperature-precipitation, slow-diffusion carbides" instead of "high-temperature-precipitation, fast-diffusion carbides". During sintering, the carbon solubility is high enough to dissolve all carbon atoms in the titanium matrix. However, during cooling, a rather complex process of precipitation and repeated dissolution occurs due to the special shape of the Ti-C phase diagram. Thus, it is necessary to control the precipitation-related processes as precisely as possible.

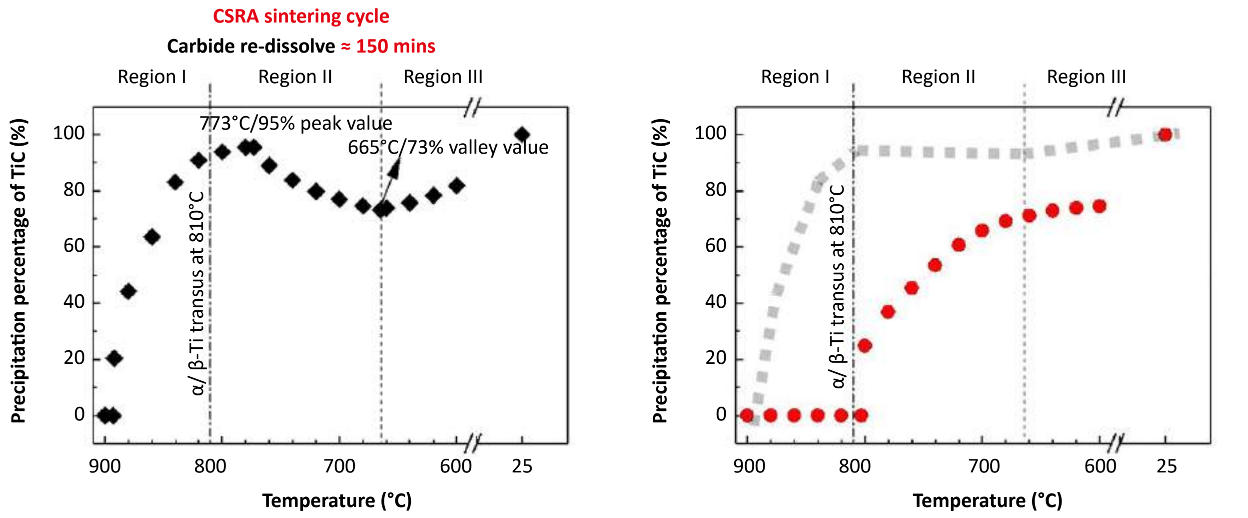


Fig. 8 Changing the amount of carbides in Ti-20Nb-10Zr during different processing. The grey curve on the right is the standard sintering cycle, the black curve on the left the special CSRA cycle. The red curve on the right refers to the effect of an addition of 0.1 wt.% Y [4]

Xu's strategy was to prolong the time for the re-dissolving of the carbides, creating nucleation sites inside the beta grains and providing low diffusivity for carbon atoms through the low temperature and the hexagonal crystal lattice. Fig. 8 left shows the effect of the special sintering cycle on precipitated carbides, measured by means of synchrotron diffractometry. This process was combined with the addition of an oxygen getter, namely 0.1 wt.% Y. Y scavenges oxygen from the grain boundaries and the matrix, thus changing the phase diagram in such a way that precipitation of carbides occurs at lower temperatures (Fig. 8 right).

> *"Xu's strategy was to prolong the time for the re-dissolving of the carbides, creating nucleation sites inside the beta grains and providing low diffusivity for carbon atoms through the low temperature and the hexagonal crystal lattice."*

The combination of these measures led to the precipitation of small carbides inside the grains as intended. Through this method, fracture elongation was improved from 6.5% to 10.7%, but UTS decreased from 945 MPa to 904 MPa, which is still a very good value. Whether the procedure can be transferred to other beta titanium alloys is not yet clear. However, if it can be transferred, a rather easily applied solution to a general problem for the MIM of titanium may be achieved.

Processing beta alloys with the blended powders approach

Beta titanium alloys were also the topic of Orest Ivasishin, from the International Center of Future Science, Jilin University, Changchun, China, and G. V. Kurdyumov Institute for Metal Physics, Kyiv, Ukraine. Here, the aim was to lower the costs of the alloys without a deterioration of mechanical properties. Technical alloys such as Ti-5Al-5V-5Mo-3Cr (Ti-5553), Ti-10V-2Fe-3Al (Ti-1023) and Ti-1Al-8V-5Fe (Ti-185) as well as medical alloys of the systems Ti-Zr-Nb and Ti-Zr-Nb-Ta were the subject of investigation.

The basic approach of Ivasishin was to use hydrogenated powders and blend elemental powders and/or masteralloy powders. The processing cycle was powder blending, compaction and sintering. The use of TiH_2 powders is an approach which is currently quite popular, as one of the advantages lies in the brittle behaviour of the hydrides; the powders are crushed during pressing, fresh surfaces are formed and a 'locked' compact with high green density is created. In addition, mechanisms such as fast diffusion and sintering are enabled during dehydrogenation because of the formation of a high number of crystal defects.

This powder blending approach works well for alloys such as Ti-6Al-4V with low volumes of alloying powders and high processing temperatures (high beta transus). Conversely, the processing of beta titanium alloys raises the problem

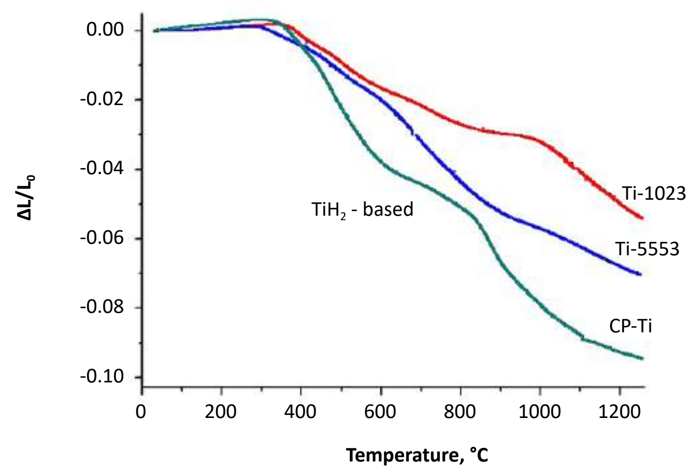


Fig. 9 Shrinkage of two beta alloys made from a blend of TiH_2 and alloying elements compared to pure TiH_2 [5]

of high amounts of alloying powders, slow dissolution and diffusivity of heavy elements and a risk of Kirkendal porosity. Chemical inhomogeneity and relatively high porosity is usually the consequence. Furthermore, the different volume changes of TiH_2 and alloying powders during dehydrogenation is a source for additional voids or gaps. Fig. 9 shows that the shrinkage of beta alloys made from TiH_2 and alloying powders is much lower than that of pure TiH_2.

As a first improvement, masteralloy powders instead of elemental powders and Ti as matrix were used, both fine size fractions. Then, sintering densities around 98% were achieved for Ti-1023 [6]. With this approach, standard specifications for Ti-5553 and Ti-1023 could be exceeded. However, not all masteralloys can be refined and fine powders bear the risk of higher contamination.

In contrast, Ivasishin and colleagues successfully used fine masteralloy powders, but with TiH_2 powder as matrix. In this case, the matrix powder crushed during pressing, so it did not need to be so fine as a starting material. Furthermore, they developed an extended hydride approach, introducing all powders used as hydrides. In this case, the compaction, dehydrogenation and sintering behaviour of the powders are similar. Because all of the powders are crushed during pressing, it is not necessary to incorporate any fine powders. On the

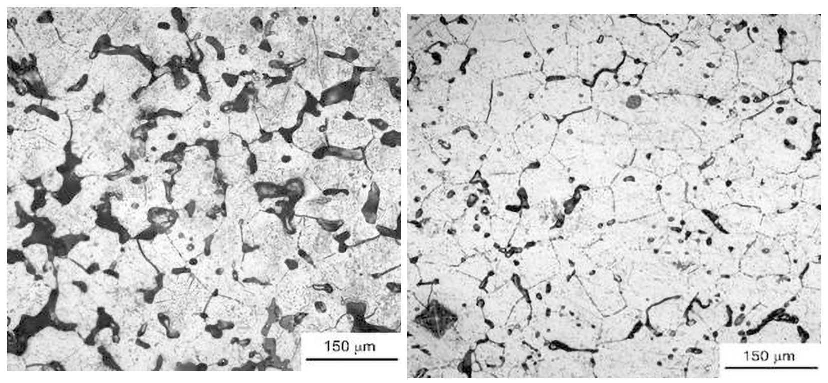


Fig. 10 Left: microstructure of a powder blend of TiH_2 + ZrH_2 plus elemental Nb. Right: microstructure of same alloy but using hydrogenated Nb (as Ti-Nb (H) master alloy) [5]

other hand, not all elements form hydrides. However, most of the typical beta stabilizers like V, Zr, Nb and Ta do so. As an example, a mixture of TiH_2 and hydrogenated Al-V-Fe was successfully processed and showed much better densification than with non-hydrogenated alloying powder.

Ivasishin transferred this approach to a Ti-51Zr-18Nb (at.%) and a Ti-26Zr-18.5Nb (at.%) medical alloy with very low Young's modulus, around 40 GPa. Here, Zr showed a hydrogenation behaviour similar to Ti. However, relatively high porosity was still an issue. After additional hot deformation, the Ti-51Zr-18Nb revealed excellent properties; thus, the porosity was the sole problem. A solution was found by using Nb in a hydrogenated masteralloy, namely in Ti-Nb and Zr-Nb. The latter, in particular, led to a fine and uniform porosity of only 2%. Fig. 10 shows the big difference in sintering behaviour using elemental Nb (left) and hydrogenated Nb in the form of a Ti-Nb (H) master alloy.

Additionally, the processing of Ti-7Zr-34Nb-5Ta-2Si succeeded by utilising the approach of hydrogenated powders and led to excellent mechanical properties [7]. Here, Si preserved the fine grains during sintering. However, mechanical alloying was performed for a very long time, followed by sintering. Ivasishin *et al* processed a similar composition (without Si) by blended elemental Powder Metallurgy using the extended hydride approach – again with success. Because of Ta, a two-step hydrogenation had to be applied. Thus, in general, faster sintering at lower temperature is possible by application of the extended hydride approach. As a result, both energy and cost can be saved.

Development of a low-cost alloy

A further presentation on cost reduction was given by Leandro Bolzoni, from the University of Waikato, New Zealand. Bolzoni pointed out that a cost reduction for the final titanium part of 30–50% is necessary to

increase competitiveness with other metals such as steel or aluminium. His approach, as part of the Titanium Technology New Zealand (TiTeNZ) research programme sponsored by the New Zealand Ministry of Business, Innovation, and Employment, is to develop novel titanium alloys using elements that are as cheap as possible and combine this with low-cost production processes. His choice for this combination was a Fe-bearing beta-eutectoid titanium alloy and thermomechanical powder consolidation (TPC). This process comprises powder mixing, compaction by sintering or hot pressing and final compaction by extrusion, forging or rolling. The aim is to achieve mechanical properties equivalent to wrought alloys but with significantly lower costs.

The potential of Fe for stabilising the beta phase is about 2.5-fold higher than that of Mo. Furthermore, the solubility of Fe in Ti is rather high, offering a wide range of property control. Fe is cheap and is recognised as a sintering aid because of its 3-5 fold higher diffusivity than titanium. Bolzoni reported on a method to create nanostructured Fe-bearing titanium alloys by slow bainitic decomposition. In this case, both alpha-Ti and TiFe precipitates are formed in the beta-matrix during appropriately developed heat treatments. Fig. 11 shows a comparison of the hardness between different titanium alloys. The very high hardness of Ti-5Fe is equivalent to a much more expensive alloy containing Mo and Cr.

In the second part of his presentation, Bolzoni focused on processing. The potential for cost reduction as well as for the optimisation of mechanical properties in this field is high. For example, processes such as induction sintering shorten sintering time significantly, thus minimising the time for oxygen pickup and grain growth. Through the appropriate selection of processing parameters (i.e. green density ≥ 90%, sintering temperature ≥ 1000°C and sintering time ≥ 0 s), density, tensile and mechanical properties comparable to vacuum sintering are achieved. Thus, processing should be adapted to the requirements for

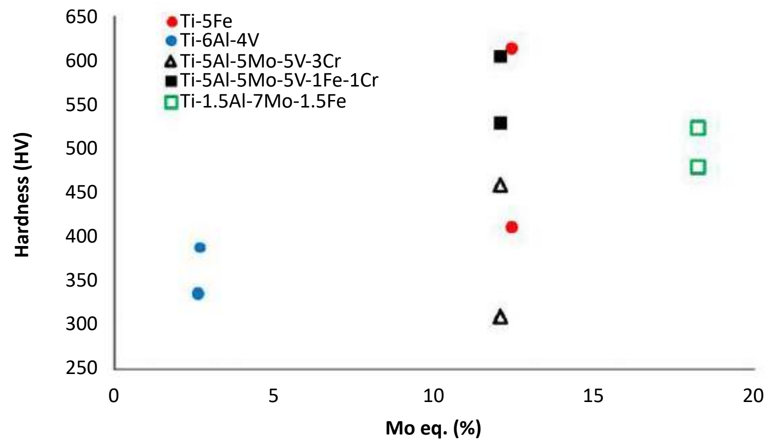


Fig. 11 Comparison of the hardness between different titanium alloys, including Ti-5Fe [8] [9]

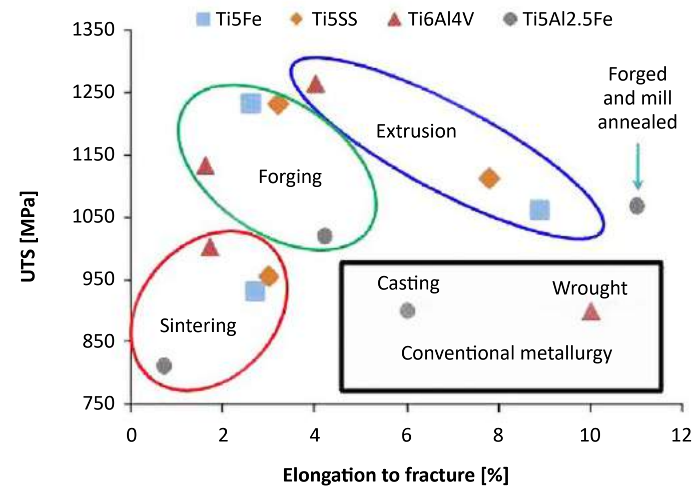


Fig. 12 Comparison of tensile properties of different titanium alloys [9]

the application to minimise costs. Furthermore, Bolzoni pointed out the importance of microstructure for fatigue; bimodal structures usually have the best fatigue properties and can be adjusted through thermomechanical processing. A solid understanding of the relationship between processing, microstructure and properties is necessary. This knowledge was applied to Fe-bearing alloys, as shown in Fig. 12. Similar, or in some cases even better properties were achieved in Ti-5Fe compared to Ti-6Al-4V. Fatigue tests revealed an endurance limit of 625 MPa at 10^7 cycles for Ti-5Fe.

Further tests were performed on Ti-7Fe. The environmental response (corrosion/oxidation) was compared between sintered and extruded material. The tests reveal a better performance of the extruded alloy and an oxidation behaviour similar to that of pure titanium. In summary, the approach of combining alloy and process development to a low-cost route appears to have great potential. However, the results show the high importance of generating in-depth scientific understanding of materials and processes if industrial implementation is the end goal.

Black Ti Alloy	UTS (ksi)	Yield (ksi)	Elongation (%)
Ti-1.5Sn-30Zr-2Mo	155	132	16
Ti-1.5Sn-30Zr-2Mo - Blackened	150	132	13
Ti-1.5Sn-30Zr-4Mo	164	140	10
Ti-1.5Sn-30Zr-4Mo - Blackened	157	140	8
Ti-1.5Sn-30Zr-6Mo	168	147	9
Ti-1.5Sn-30Zr-6Mo - Blackened	160	146	4

Table 1 Current status of development of a novel black titanium alloy with high mechanical properties and MIM compatibility [10]

MIM of black titanium alloys

Black titanium is the term for titanium-based alloys with a substantial content of zirconium. The surface oxides formed can give the part a blue or black colour, depending on the exact oxidation process. Paul Sheffield, Praxis Technology, USA, presented on the ongoing development of a black titanium alloy suitable for MIM processing. One motivation to use black titanium is its significantly higher wear resistance compared with Ti-6Al-4V. This wear resistance is comparable to titanium coated with diamond-like-carbon (DLC), and thus ideally suitable to application in replacement knees or hips.

Sheffield started his presentation with an overview of existing alloy compositions. Typically, these are either binary Ti-Zr or beta-stabilised Ti-Zr-β alloys. At a basic level, the limitations of black titanium are high costs, low strength and the potential for poor properties when PM processed, heat treated, then blackened. The aim is, therefore, to develop a novel alloy adapted to the needs of both the customer and MIM.

Generally, conventional beta-stabilised alloys have better properties. However, they can lose strength due to the blackening thermal cycle degrading the improvements in mechanical properties achieved by heat treatment of the alloy. One commercially available alloy is Ti-35Zr-10Nb. As a wrought material, UTS is around 1030 MPa (150 ksi). After furnace cool and blackening, UTS is reduced to 840 MPa. Sheffield and his colleagues looked to combine the alpha phase based Ti-Zr system with the beta-stabilised one and create a new alpha/beta alloy with high wear resistance, which will maintain good mechanical properties after blackening.

Thus, Al was first added as a stronger alpha-stabiliser, leading to the successful result that blackening no longer lowered strength. The response to the blackening process was even improved, meaning the part goes to a deeper dark colouring, which was a demand from the customer. In a following step, Nb was replaced by Mo as it is cheaper and more effective with regard to blackening response. Furthermore, Sn replaced Al as alpha-stabiliser and Mo was varied between 2 and 6 wt.%. The current status of materials development is shown in Table 1.

The results appear promising. The mechanical properties tend to be better than those of the conventional alloys and the loss of strength after blackening is small. In principle, alpha/beta alloys have a good sinterability and good wear resistance.

Sintering under hydrogen

Hydrogen is not just a sintering aid, when it is used to form metal hydrides as mentioned before. Sintering of 'normal' powders under hydrogen was mentioned in several presentations at the conference. The idea is to exploit the effect for grain refinement by the introduction of a temporary additional phase, namely the TiH_2 phase, and a change in beta transus, varying with the hydrogen concentration.

The process has primarily been developed over the last decade by Zak Fang's group at the University of Utah in relation to Ti-6Al-4V via a process called Hydrogen Sintering and Phase Transformation (HSPT). The material is hydrogenated, sintered and dehydrogenated again under a controlled hydrogen atmosphere. Chengshang Zhou, from the State Key Laboratory of Powder Metallurgy, Central South University Changsha, China, explained in his presentation how to utilse the change of volume connected with the hydrogenation process to densify PM titanium alloys.

Hydrogen induces expansion of the titanium matrix lattice. Thus, the idea is to constrain this expansion in a rigid cell and utilise the developing compressive stress to densify the powder compact or the sintered part. After hydrogenating, a dehydrogenating process takes place (Fig. 13). The process is called Constraining Thermal Hydrogen Process (C-THP).

Zhou explained the necessary conditions for a successful process. 2 wt.% hydrogen induces about 7 vol.% expansion, thus, the material has to be deformable, no brittle hydride phases should be present to avoid cracks. Therefore, the process parameters were carefully chosen according to the Ti-H phase diagram. In the presented work, Zhou compared titanium powder sintered conventionally and processed by C-THP. As powders he used HDH Ti powders as well as TiH_2 powders, both with a size smaller 200 mesh. XRD experiments proved that the TiH_2 phase was present only during the process steps utilising hydrogen. The sintered samples showed significant increase in density by 2-8% after application of C-THP. The highest improvement was observed with originally low density samples, e.g. density of ~84 % increased to ~92%. In addition, almost full density of 99.8% was achieved by use of TiH_2 powders and C-THP processing (Fig. 14).

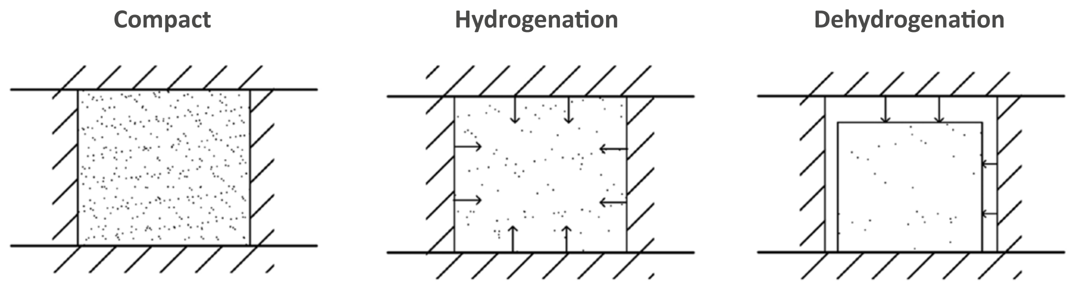


Fig. 13 After compacting the powder in a rigid cell, hydrogen is let in and the induced volume expansion results in compressive stress enhancing densification. After the process the material is dehydrogenated again [11]

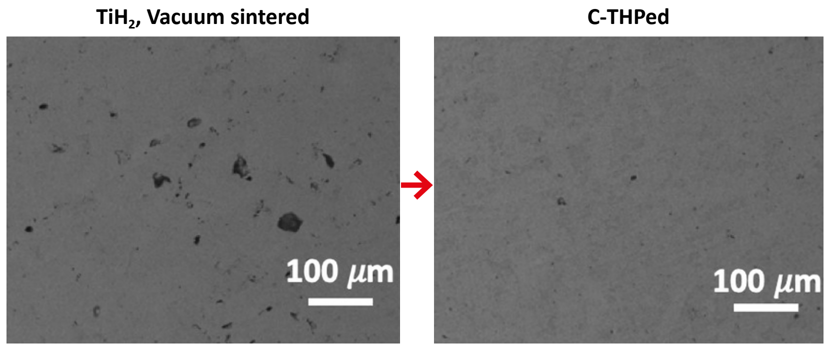


Fig. 14 Comparison of porosities without and with C-THP application [11]

Thus, the C-THP method appears to be very promising with respect to achievement of near-full density during sintering. With further micrographs, Zhou even proved a very homogeneous distribution of remaining pores.

MIM and HSPT

HSPT was also applied as one method for grain refinement in the presentation by Wolfgang Limberg, Helmholtz-Zentrum Geesthacht, Germany. Limberg discussed measures for grain refinement in MIM Ti-6Al-4V in order to improve fatigue behaviour. As already mentioned, grain growth is a basic challenge during sintering, deteriorating mechanical properties and, in particular, fatigue behaviour. To overcome this problem, Limberg considered three different approaches:

- Grain boundary pinning during sintering in beta phase by addition of dispersives,
- Using very fine powders and sintering temperatures around the beta transus (SBS process),
- Post-processing of MIM material by HSPT

For the first approach he used gas atomised Ti-6Al-4V powder < 45 µm and added 0.5 wt.% Y and 0.5 wt.% B, respectively. Sintering parameters were 2 h at 1400°C. The same powder was used in the third approach. However, the powder was just pre-sintered for 30 min. at 1300°C and then processed by HSPT at the University of Utah. For the second approach, < 20 µm powder was used and processed at Element 22 GmbH, as previously described. Limberg achieved rather different microstructures (Fig. 15). Compared to the pure Ti-6Al-4V powder (left), the boron addition in particular led to significant grain refinement (middle). HSPT had a dramatic effect on grain size and structure as visible in Fig. 15, right. The microstructure after SBS processing was presented in Fig. 5.

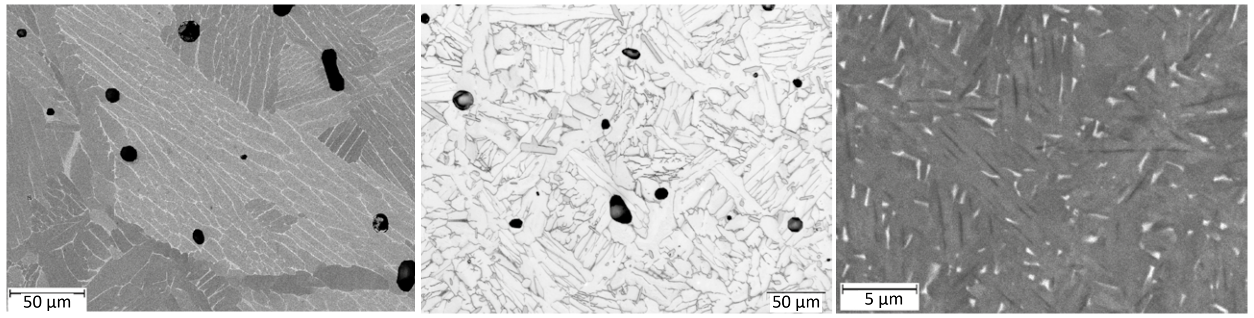


Fig. 15 Micrographs of Ti-6Al-4V (left), Ti-6Al-4V-0.5B (middle), Ti-6Al-4V + HSPT [12]

Specimen type	Yield strength [MPa]	Ultimate tensile strength [MPa]	ε_f [%]	Fatigue strength [MPa]
MIM-Ti-6Al-4V	771	884	15.3	450
MIM-Ti-6Al-4V + 0.5 wt.-% Y	692	794	12.8	465
MIM-Ti-6Al-4V + 0.5 wt.-% B	787	902	11.8	650
MIM-Ti-6Al-4V (SBS)	893	985	20	640
MIM-Ti-6Al-4V + HSPT	976	1028	14.2	775
Minimum ASTM B348 Grade 5	828	895	10	

Table 2 Comparative results for tensile and fatigue properties of the differently processed alloy Ti-6Al-4V [12]

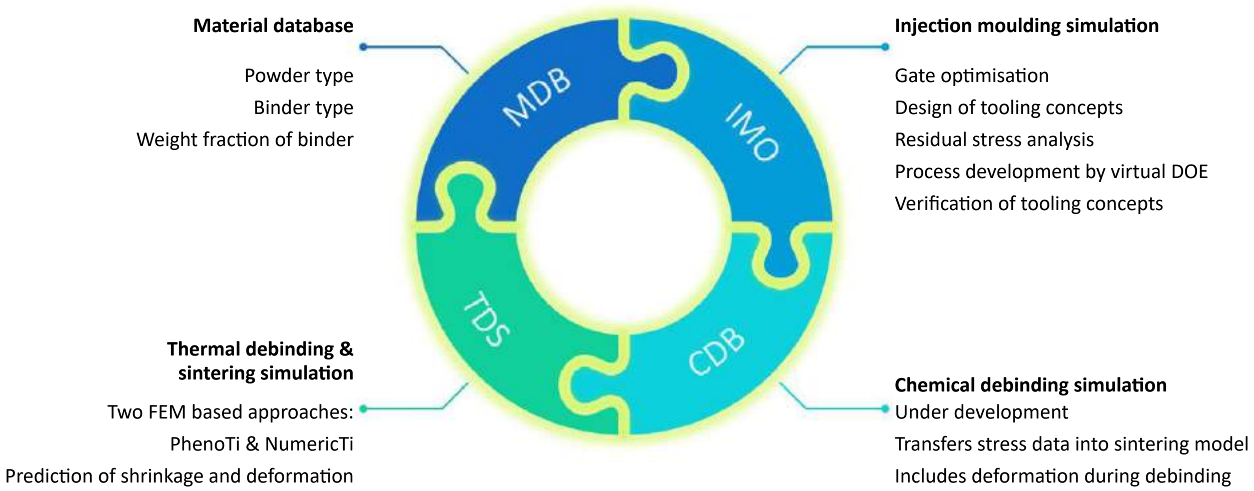


Fig. 16 Scheme of simulation modules for MIM [13]

Table 2 shows the tensile properties and fatigue limit (4-point bending test, 10^7 cycles) of the differently processed alloy. Obviously, the fatigue limit is well related to the size of the microstructure.

The results show that a variety of possibilities exists to improve the fatigue behaviour by grain refinement. Here, HSPT appears to be an excellent process. However, it is an additional step which means additional costs. Therefore, Limberg suggested in his summary to combine MIM and HSPT in one single process. It was also suggested that a combination of SBS and HSPT could be worthwhile investigating.

Modelling of MIM

As mentioned at the start of this report, it appears that the number of presentations on MIM is slowly decreasing, perhaps because the process is now in commercial production and, as a result, there are fewer basic research questions. For commercial applications, however, the prediction of feedstock behaviour during injection moulding, of deformation during shrinkage and finally of mechanical properties and their dependence on processing parameters is essential to reduce the cost of new part development. Matthias Scharvogel, Element 22 GmbH, presented the activities of his company in this field. The final aim is to simulate the whole MIM process in advance, reducing development times for tool and process parameters (Fig. 16).

Scharvogel presented the application of two modules developed by Element 22 and used as sub-routines of commercial modelling packages. PhenoTi is a set of fictional materials parameters used in a commercial Finite Element Method (FEM) package for sintering simulation. NumericTi is a subroutine for the prediction of shrinkage and deformation hotspots. Scharvogel pointed out that simulations are already used in the company as helpful tools for cost reduction and customer consulting. He further highlighted the importance of high quality experimental data as input for the simulation. Comprehensive and sophisticated tests are needed to obtain useful and reliable results. For example, testing is performed with a variety of samples with different densities to cover the whole range of practical tolerances.

Flexibility of binder-based sintering

MIM is an established and dynamic technology; however, the one drawback is the need for a mould. The MIM

| contents page | news | events | advertisers' index | contact |
PMTi2019 conference report

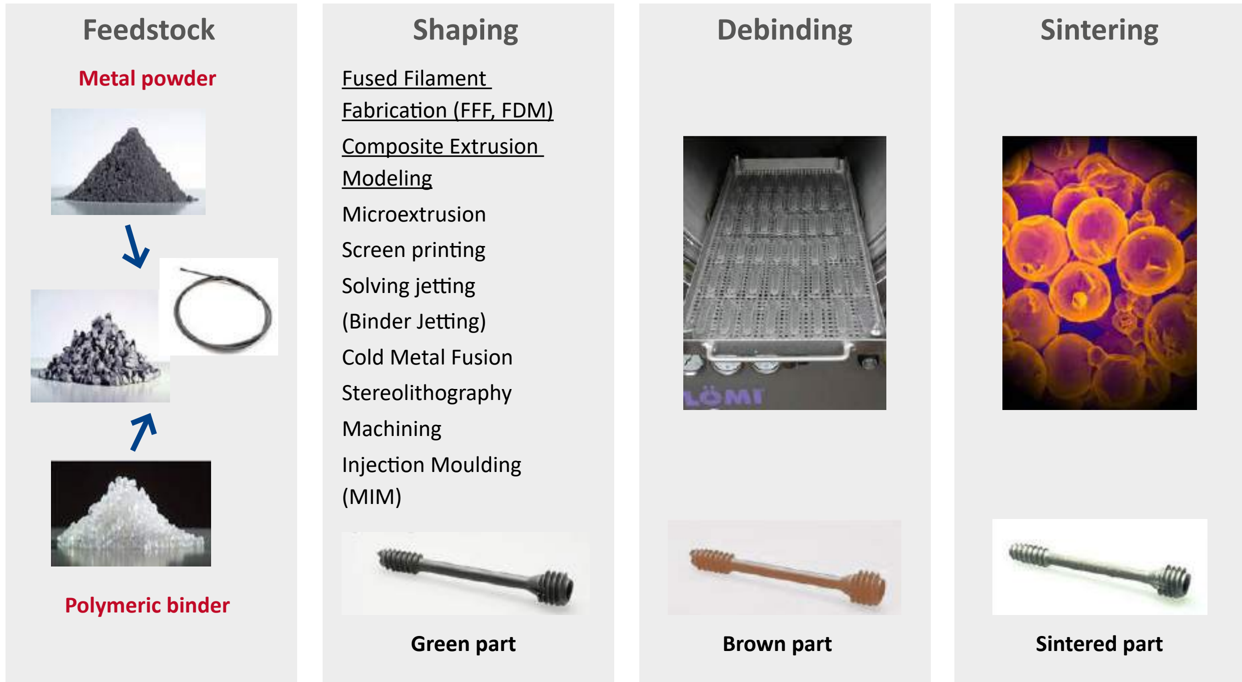


Fig. 17 Scheme of feedstock-based processing - the shaping step is very flexible [14]

of prototypes or small series runs is expensive and takes a lot of development time. However, if prototypes are manufactured by other processes, the risk that later MIM production leads to different properties or tolerance issues is rather high. Currently, increasing interest can be observed in technologies based on feedstock and sintering, but without the need for a mould. The author of this report gave an overview of such technologies in his presentation.

In my presentation, I pointed out the advantage of sintering to achieve homogeneous microstructures and the necessary properties in prototype or small-series parts. In comparison, local melting, as used in L-PBF, leads to highly complex microstructures along with stresses inside the part. The use of a feedstock and sintering makes it rather simple to change the shaping process without changing the microstructure, as Fig. 17 shows.

In my presentation, I introduced several shaping technologies, some of them well known from polymer Additive Manufacturing. An example was Fused Filament Fabrication (FFF), also known as Fused Deposition Modelling (FDM), a standard process for simple 'domestic' 3D printers. However, instead of pure polymers, metal powder-filled filaments are used. After printing, the part is debound and sintered, just as in the MIM process. Fig. 18 shows an example of an FFF part made from Ti-6Al-4V.

While FFF needs filaments as feedstock, other technologies like Composite Extrusion Modelling (CEM) use the same granules as MIM. Here, a small extruder directly 'prints' the part layer by layer, making fine details possible. Even

Fig. 18 Demonstrator gear fabricated by FFF from Ti-6Al-4V powder (Binder system developed by Emery Oleochemicals GmbH, Germany. Debinding and sintering by Element 22 GmbH, Germany) [14]

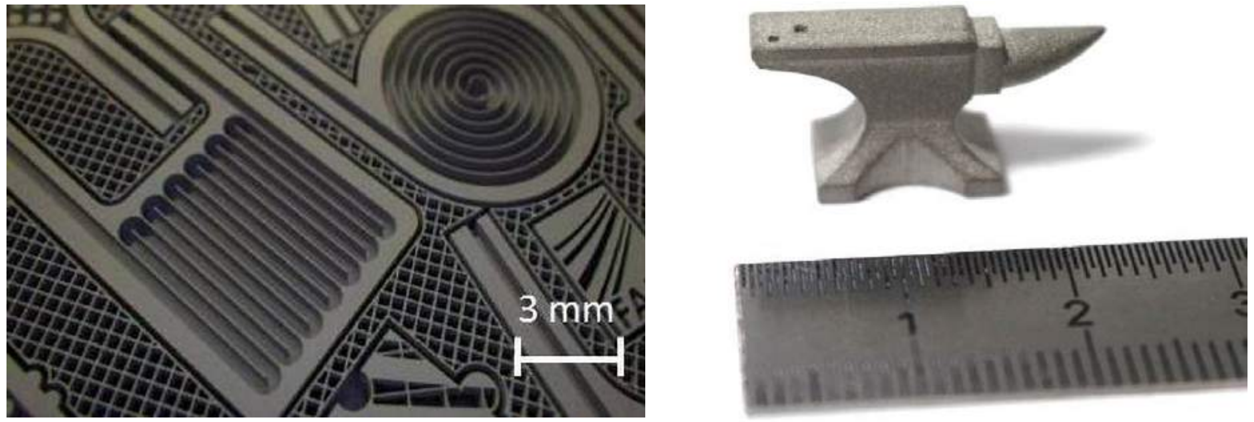


Fig. 19 Left: demonstrator part made by screen printing from titanium (Fraunhofer IFAM Dresden, Germany). Right: demonstrator part made by lithography from titanium (built by Incus GmbH, Austria, sintered at Element 22 GmbH, Germany) [14]

screen printing is possible. In Fig. 19 (left) a highly detailed structure is shown made from fine titanium powders (< 22 μm).

A further technique introduced to realise comparably fine details was lithography (Fig. 19, right). Here, a photosensitive resin filled with metal powder is used and the part is 'printed' layer-by-layer and hardened by light. All of these processes are appropriate for the production of single parts or small series.

Binder Jetting is the technology which offers the greatest possibility for high-volume production. The principle is similar to L-PBF in that it is a powder bed process. However, rather than a laser melting the powder, a print head is used to jet binder onto the powder layers. After production, the parts are debound and sintered.

I also pointed out that not all of these technologies are developed sufficiently that commercial production is yet possible. In many cases, there are still some issues relating to the delamination of printed layers, pores, cracks and high tolerances. Thus, further technical development is needed. Additionally, in most cases, titanium processing is not officially offered by the majority of systems. On the other hand, clear statements that titanium processing is under development have been made at several conferences.

Technologies such as Binder Jetting are ready to produce high numbers of parts in a relatively short time. One major advantage of these processes compared with L-PBF is the often significantly lower investment for the equipment. In addition, they are perfect supplements for MIM suppliers, because the debinding and sintering equipment already exists at these companies. Thus, it can be expected that these alternative AM processes will become established in the next few years, including for the production of titanium parts.

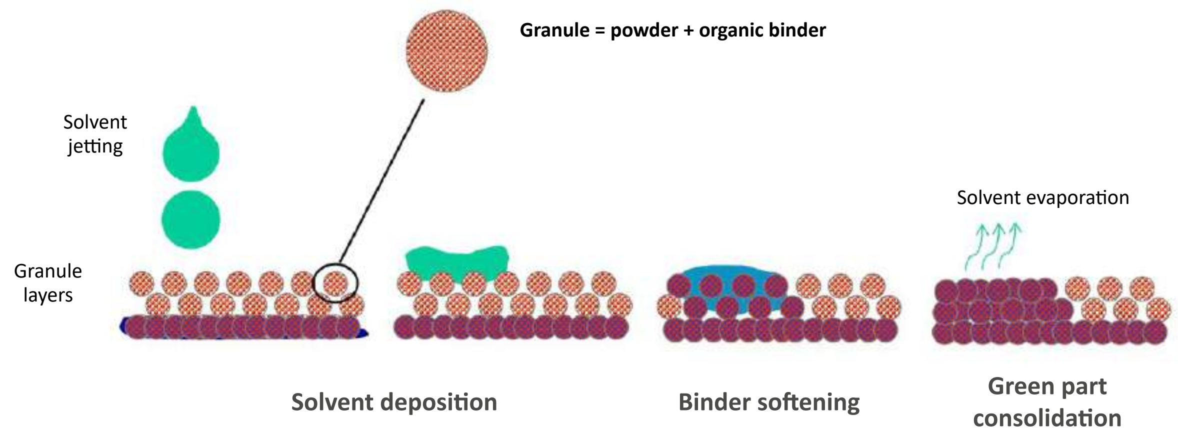


Fig. 20 Schematic of solvent on granule Additive Manufacturing [15]

Additive Manufacturing by Solvent Jetting on granules

Efraín Carreño-Morelli, from the University of Applied Sciences and Arts Western Switzerland, presented a further binder-based AM technology. Compared with Binder Jetting, rather than using a bed of powder, a bed of granules is used that consists of powder particles and binder. Instead of binder, a solvent is jetted by the print head (Fig. 20). Then, the binder is dissolved and bonds the neighboured granules together. After printing, the usual debinding and sintering process is conducted. As an advantage only a low viscosity solvent has to be jetted while in the case of binder jetting high viscosity, drop size and printhead cleaning are crucial issues. Furthermore, the tolerance to powder morphology is very high, even irregular powders can be used, because the granules are near-spherical and exhibit improved spreadability.

Carreño-Morelli combined this technique with the processing of TiH_2 for cost-reduction purposes. He pointed out that, during dehydrogenation, not only hydrides but even elemental hydrogen occurs, which is able to react with oxides on the surface of the titanium powder to form water molecules, which are evaporated. Thereby, a reduction of the oxygen content is possible.

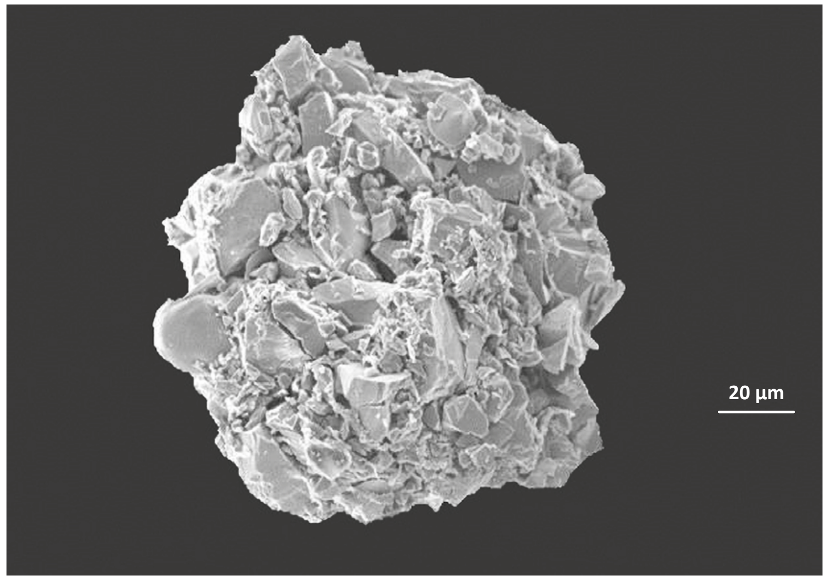


Fig. 21 Granule made from TiH_2 powder and polymer binder [15]

The granules were made by the wet mixing of powder, binder and solvent followed by drying, milling and sieving. Fig. 21 shows one of the granules produced.

As examples, Carreño-Morelli printed porous electrode plates (Fig. 22, left) as well as prototypes of watchcases (Fig. 22, right). The latter parts were sintered at 1200°C to achieve reasonable density, while the sintering temperature of the porous electrodes was 900°C. The results show the potential of this flexible technology, also for titanium processing.

Extrusion of feedstock

Finally, Johannes Schaper, Element 22 GmbH, presented initial results from a feasibility study to process feedstock by extrusion. The idea is to provide a low-cost method to produce geometries such as thin-wall or multi-lumen tubes or sheets or other profiles from titanium alloys which are difficult to deform, such as Ti-6Al-4V. Because these alloys cannot be cold-deformed, rather significant efforts have to be performed for production, including removal of

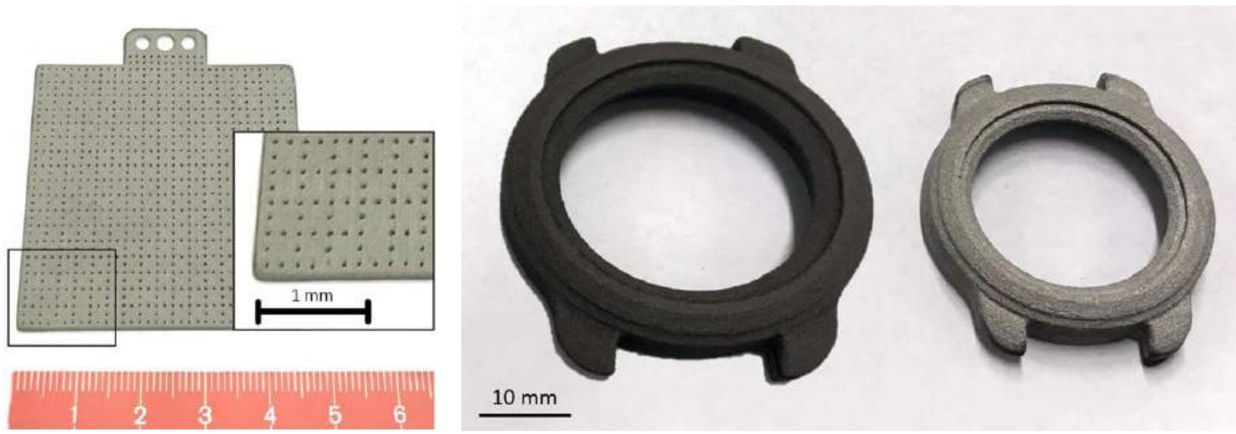


Fig. 22 Left: porous electrode plates, right: experimental watch case, both made by solvent printing on TiH_2 based granules [15]

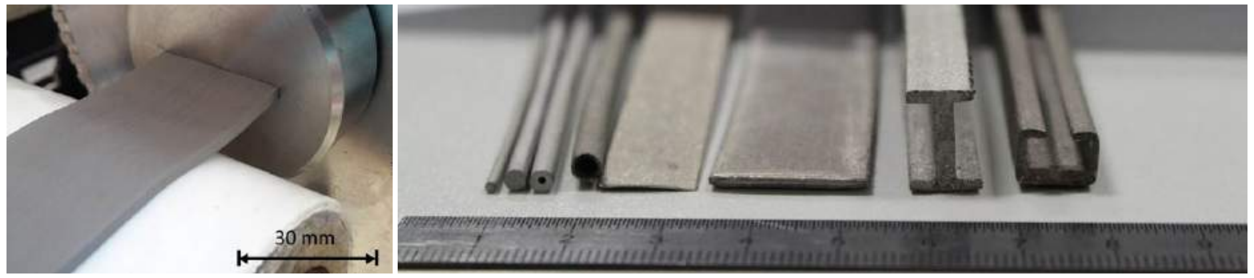


Fig. 23 Left: production of a thick sheet by extrusion of MIM feedstock, right: variety of profiles produced [16]

oxidised surface layers. Schaper and his colleagues used a conventional extruder to process the feedstock. In Fig. 23 (left) the fabrication of a thick sheet with rectangular cross section is shown.

Fig. 23 (right) shows the variety of profiles that have now been fabricated by extrusion. Sheet thicknesses below 0.5 mm have been achieved, along with wall thicknesses of between 0.4 mm and 5 mm, channels smaller than 1 mm were realised in a tube with 3 mm diameter and wires with a diameter below 1 mm. To date, the maximum length produced is 720 mm because of the size of the available furnace. Again, this study confirms the flexibility of the powder-binder approach following by sintering. Schaper ended his presentation with the results of mechanical tests, showing results equivalent to MIM parts.

Summary

In summary, PMTi proved itself once again as an unrivalled conference series on the highly topical subject of titanium powder processing. Fatigue was one of the most mentioned topics across the presentations; this shows that demanding application areas, such as aerospace and medical devices, remain a key target. The clear message of the conference was that this is also true for sintered parts – sintering will remain as one of the most important manufacturing processes along with L-PBF.

Author

Dr Thomas Ebel
Institute of Materials Research
Division Metallic Biomaterials
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research
Max-Planck-Straße 1
21502 Geesthacht
Germany

Tel: +49 4152 87 1944
thomas.ebel@hzg.de
www.hzg.de

References

[1] Randall German, Titanium Sintering - From Atomic Motion to Production Cycles, as presented at PMTi2019

[2] I.M. Robertson, G.B. Schaffer, Review of densification of titanium based powder systems in press and sinter processing, *Powder Metallurgy* 53 (2010), 146–162

[3] Johannes Schaper, Microstructural Optimization of Ti-6Al-4V PM Parts, as presented at PMTi2019

[4] Peng Xu, TiC Reprecipitation Improving Ductility of Beta Titanium Alloys Processed via MIM, as presented at PMTi2019

[5] Orest Ivasishin, Titanium Hydride Approach in Powder Metallurgy of Aerospace and Medical Beta Alloys, as presented at PMTi2019

[6] Y.F.Yang, S.D.Luo, G.B.Schaffer, M.Qian, *Materials Science and Engineering* A, 528, (2011), 6719-6726

[7] Y.H. Li, C. Yang, F. Wang, H.D. Zhao, S.G. Qu, X.Q. Li, W.W. Zhang, Y.Y. Li, *Materials and Design* 85 (2015) 7–13

[8] C. Romero, S. Raynova, F. Yang, L. Bolzoni, *Journal of Alloys and Compounds*, 769 (2018) 226-232

[9] Leandro Bolzoni, Cost-Affordable Ti: Thermomechanical Powder Processing of Low-Cost Compositions, as presbented at PMTi2019

[10] Paul Sheffield, Black Titanium Alloy Development, as presented at PMTi2019

[11] Chengshang Zhou, Using Hydrogen-Induced Lattice Expansion to Densify Powder Metallurgy Titanium Alloys, as presented at PMTi2019

[12] Wolfgang Limberg, Effect of Microstructure on the Fatigue Properties of MIM Ti-6Al-4V, as presented at PMTi2019

[13] Matthias Scharvogel, Simulation of Metal Injection Molding of Titanium Alloys, as presented at PMTi2019

[14] Thomas Ebel, From MIM to AM: the Flexibility of Binder-Based Sintering Technologies, as presented at PMTi2019

[15] Efraín Carreño-Morelli, 3D Printing of Titanium Parts from Titanium Hydride Powder, as presented at PMTi2019

[16] Johannes Schaper, Titanium Extrudates with Outstanding Material Properties via Feedstock Extrusion, as presented at PMTi2019

Euro PM2019: Special Interest Seminar outlines competing and complementary aspects of MIM and sinter-based AM

During Euro PM2019 in Maastricht, the Netherlands, October 13–16, 2019, a Special Interest Seminar on MIM and sinter-based AM was held with the purpose of generating a better understanding of the competitive and complementary aspects of these technologies. As Dr David Whittaker reports, over the course of three presentations by Desktop Metal's Dr Animesh Bose, GKN Sinter Metals' Dr Simon Höges and Fraunhofer IFAM's Dr Thomas Hartwig, the areas in which sinter-based AM poses a threat to MIM, and those areas in which it can provide new opportunities, were considered.

Since MIM is a high-volume, low-cost production method for relatively small components, Euro PM2019's Special Interest Seminar on MIM and AM concentrated on those AM technologies that are gearing up to overlap in terms of production volumes, cost and component size, thus being a potential threat to MIM as well as offering potential synergies. Such technologies depart from the currently dominant metal AM technologies based on powder melting, instead adopting an approach involving the debinding and sintering of green bodies. As a result, they are often referred to as 'MIM-like' processes. In Maastricht, a Special Interest Seminar was held comprising three presentations from invited experts in the field.

The impact of powder-binder-based AM on MIM

The first of these presentations came from Dr Animesh Bose (Desktop Metal, USA). Dr Bose, who has a highly respected background in MIM, joined Desktop Metal in 2016 as Vice President of Research and Development to contribute his expertise to the development of the AM technologies and equipment being offered by the company. Desktop Metal's stated mission is to make metal AM accessible to engineering and manufacturing teams and, to-date, $438 million of investments have been made to bring metal AM to mass markets.

Fig. 1 The Euro PM event series is Europe's largest annual technical conference on PM, MIM and metal AM

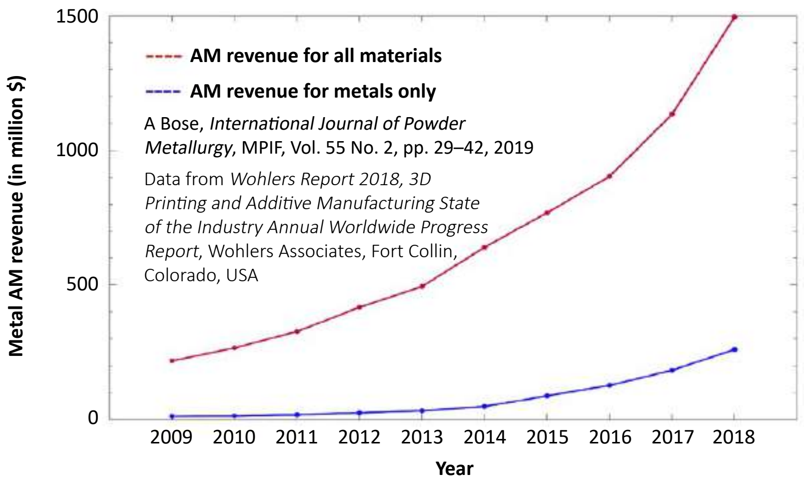


Fig. 2 Growth to date in overall metal Additive Manufacturing revenues

Fig. 3 Desktop Metal's Studio System is based on Fused Filament Fabrication technology (Courtesy Desktop Metal)

MIM and AM processes were initially compared and contrasted by Dr Bose. The similarities were identified as the use of polymer assisted processing in MIM and nearly all of the non-melt AM processes, the use of solvent debinding in MIM and several of such processes, and the use of sintering for densification in MIM and all non-melt AM processes. The one major area of distinction was the removal of the need for tooling in AM processing.

The main thrust of metal AM up to 2015 was defined as being in powder melting-based processes, where both part consolidation and geometrical shaping are combined in one forming step, producing parts with non-isotropic microstructures. Since 2015, a number of developments have led to the decoupling of the shaping and consolidation aspects of AM processing. Such processes (Binder Jetting (BJT), Fused Filament Fabrication (FFF), etc.) involve the consolidation of green bodies by debinding and sintering and therefore have similarities with MIM and can use MIM powders. These processes generally yield isotropic microstructures.

Notwithstanding the significant growth in AM revenues to date (Fig. 2), Dr Bose suggested that Metal AM had "barely scratched the surface" of its potential markets, with powder melting processes being rated as too expensive for prototyping and not sufficiently fast or cost-effective for high-volume production. The newer non-melt AM processes have been deliberately aimed at attacking these limitations, including Desktop Metal's offerings.

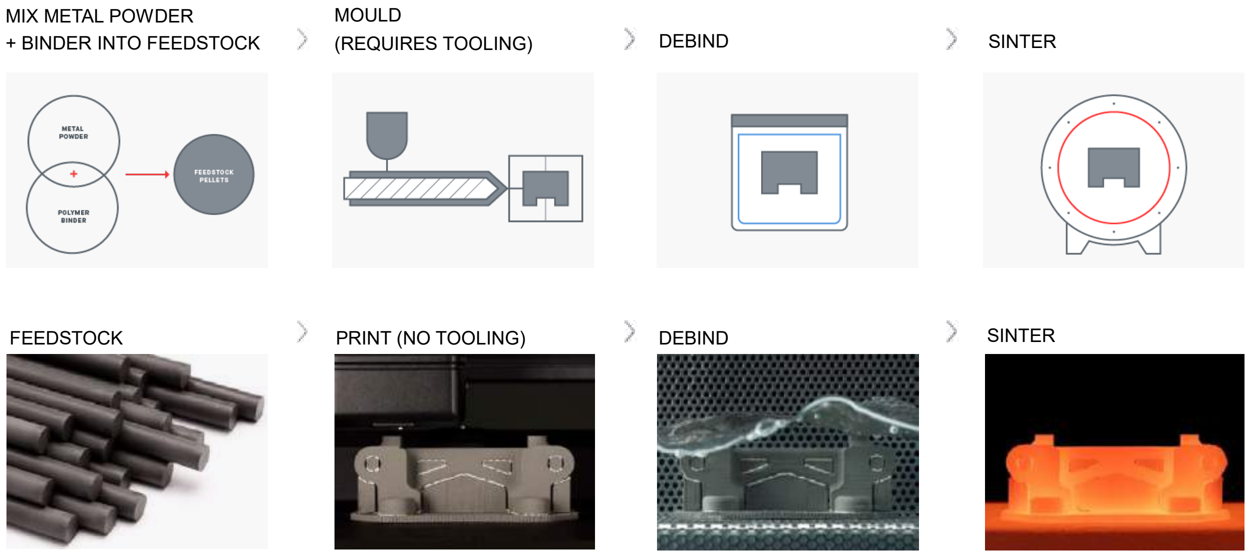


Fig. 4 MIM vs Desktop Metal's FFF process

The company's first machine, the Studio System (Fig. 3), is based on Fused Filament Fabrication, which it refers to as Bound Metal Deposition (BMD). The system is described as an office-friendly AM solution for prototyping and low-volume serial production and, in this context, is seen as being complementary to MIM.

The similarities between MIM and FFF were emphasised in Fig. 4, with both processes involving mixing of powder and binder into a feedstock (in filament form in the case of FFF), debinding and sintering. The Studio System was rated as being 'safe for the office', as no hazardous loose powder (and therefore no need for respirators or external ventilation) or high-power laser or electron beams are involved in the process. Also, no machining to remove parts from the build plate, dedicated operator or post-build stress relief are required.

Material performance data were quoted for 17-4 PH stainless steel that demonstrated that a part built on the Studio System, having 98% relative density, provided properties that exceeded the minimum requirements of the ASTM B883 standard. Various applications were presented, including a gear for earth drilling machinery (Fig. 5) and injection moulding tooling. In the latter case, the customer's investigations indicated 90% cost savings from adopting this production route.

Desktop Metal's Production System, on the other hand, employs a Binder Jetting approach and was described as a high-resolution, high-throughput metal AM technology, with much faster build rates than Laser Powder Bed Fusion (L-PBF). Binder Jetting involves the following process steps: powder spreading (layer by layer), jetting of the binder onto the powder layer, curing of the binder, depowdering, debinding/sintering, post-consolidation steps (e.g. HIP or heat treatment) and finishing operations (tumbling, polishing, blasting).

The Production System, which uses what Desktop Metal refers to as Single Pass Jetting (SPJ) technology, was described as being ideal for complex, high-performance metal parts in high volumes and as complementary to MIM, but also with the potential to pose serious competition in mass production.

Fig. 5 Gear for earth drilling machinery produced using Desktop Metal's Studio System (green state left, sintered state right) (Courtesy Desktop Metal)

"MIM companies are seen as being particularly well placed to adopt these technologies, and it has been noted that some such companies are already making proactive investments in these AM technologies."

Strategic partnership of GKN-HP-VW for Binder Additive Manufacturing

The point was made that expertise in debinding and particularly in sintering is key to the success of non-melt AM processes. Given their established expertise in this context, MIM companies are seen as being particularly well placed to adopt these technologies, and it has been noted that some such companies are already making proactive investments in these AM technologies.

A leading example of an established MIM manufacturer which is bringing its debinding/sintering expertise to bear in sinter-based AM is the GKN Powder Metallurgy

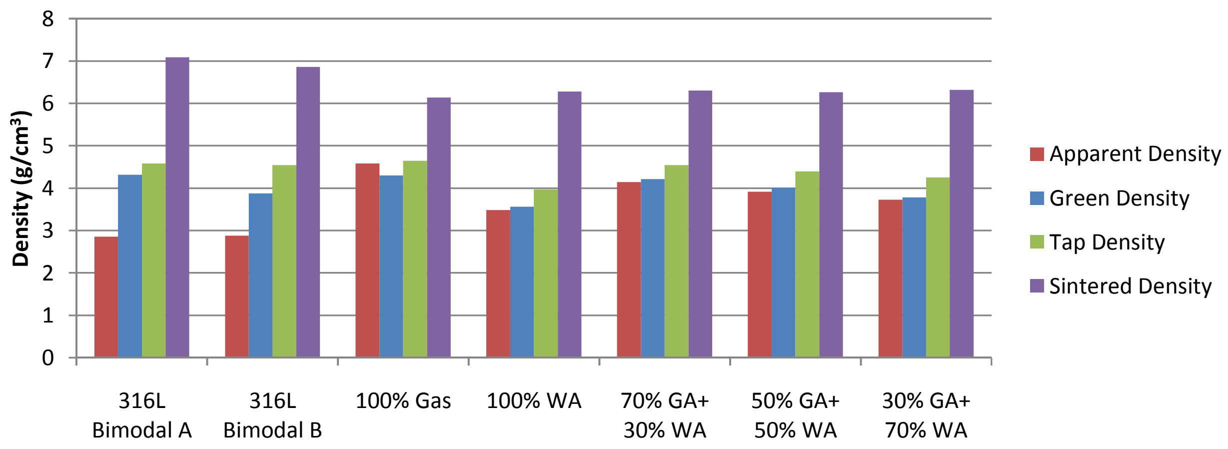


Fig. 6 Apparent density vs tap density vs green density vs sintered density for bimodal and GA/WA powder mixes processed by Binder Jetting

group. In addition, the group also has relevant strengths in conventional press and sinter PM and in bespoke powder manufacturing. In order to further their ambitions to industrialise binder-based AM for serial production, GKN has created a strategic partnership with HP and VW. Dr Simon Hoeges, Director Technology, Additive Manufacturing, GKN Sinter Metals Engineering GmbH, described the current activity within this strategic partnership.

To further their stated ambitions, the three partners have identified the need to address the full value chain: materials, design, printing, depowdering, sintering, and operational excellence.

Materials

GKN is able to leverage detailed knowledge of high-purity inert gas atomised powders, and the more cost-effective water atomised powders from within the group. In relation to powder material developments specifically for binder AM, work has explored the use of bimodal/trimodal particle size distributions to increase packing density in printing, the use of gas atomised/water atomised powder mixtures driven by the aim of reducing material costs, and the development of specific alloys to enhance sintering activity. The influences of the various particle size distributions and powder type mixture ratios on apparent density, tap density and resultant sintered density are shown in Fig. 6 for the 316L stainless steel grade.

Design

Design considerations have involved a partnership between GKN and VW. Potential automotive applications were categorised in terms of part size, described as being from 'golf ball' to 'medicine ball' sized, and part performance requirements as ranging from the purely cosmetic, through to statically loaded and dynamically loaded and 'crash relevant'.

General Binder Jetting design guidelines and specifications have been developed by the consortium, including a maximum build volume of 360 x 280 x 80 mm, a maximum part size of ~ 100 x 100 x 80 mm, wall thicknesses of between 1.5 and 30 mm, surface roughness of Rz 45 µm and mechanical properties equal or superior to MPIF Standard 35.

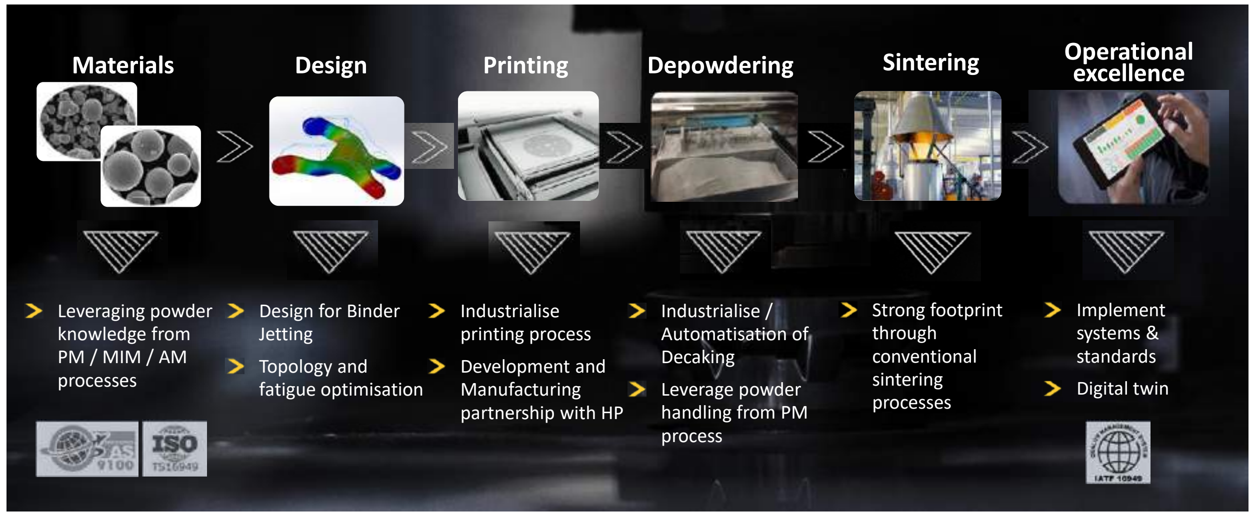


Fig. 7 How GKN Additive is able to add value in the Binder Jetting process chain

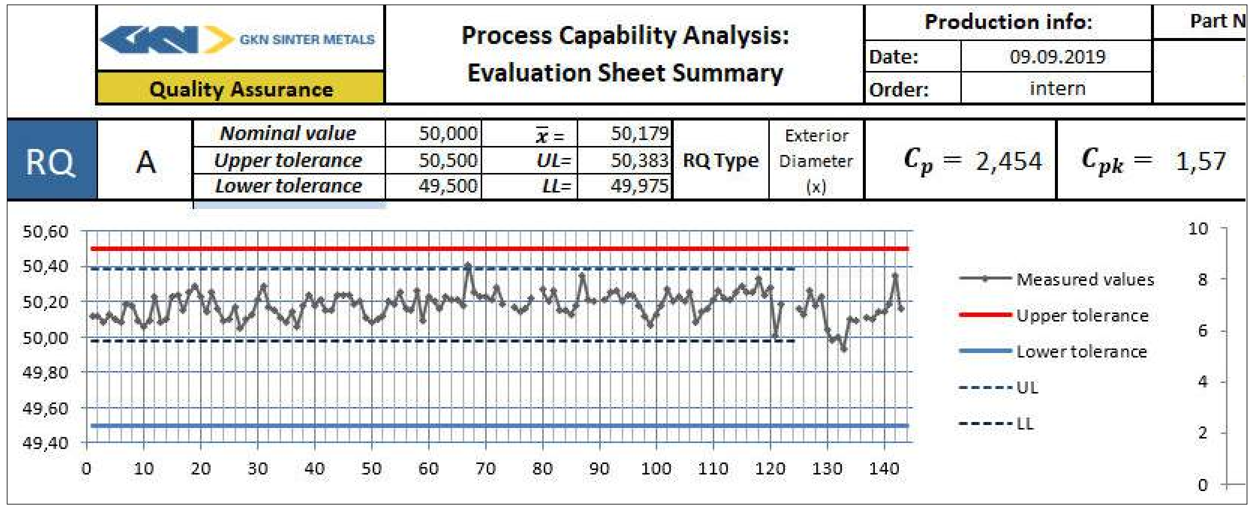


Fig. 8 Dimensional characterisation of binder jet AM parts manufactured at GKN

Printing

The direct aim of GKN Powder Metallurgy's collaboration with HP is to industrialise the AM process. Analysis of the AM process led to the estimation of current production costs for both L-PBF and Binder Jetting and the setting of future cost targets for the two technology types. It was concluded that, currently, even Binder Jetting is not cost-competitive with conventional automotive body-in-white production technologies, but this target may be achieved if a €10/kg cost level can be reached.

Consideration of powder layer spreading in the Binder Jetting process had identified that green density variations could be a problem area; however data was provided to indicate that green density could be successfully controlled to within +/- 0.05 g/cm³.

Depowdering

The aim here was to industrialise/automate the depowdering step by leveraging powder handling expertise from PM processing. At present, automation of the depowdering stage is seen as a significant industrialisation challenge, with removal of the fragile green parts from the build box currently a labour intensive process. GKN and HP are already working on a fully automated solution.

Layer	E_{mod} [GPa]	YS [MPa]	UTS [MPa]	$E_{(korr.)}$ [%]	Arch. Density [g/cc]*
1 (bottom)	180	151.56	468.07	53.49	7.79
2	168.09	150.30	462.94	53.37	7.81
3	164.16	149.08	456.58	53.14	7.81
4	175.90	152.55	468.99	53.92	7.77
5	170.76	149.31	458.76	52.88	7.78

Table 1 Mechanical characterisation of AM parts manufactured at GKN

Sintering

It was emphasised that, in this context, there was a solid foundation of expertise, involving the use of both continuous and batch sintering furnaces from conventional MIM/PM processing. The point was also made that, because binder content in Binder Jetting is, in the case of HP's technology, much lower than in MIM, only the thermal debinding step is needed.

In terms of achievable sintered properties, these have been assessed in relation to both mechanical and dimensional characteristics (Fig. 8, Table 1). As demonstrated, the dimensional characterisation included a process capability analysis.

Operational excellence

This was seen as resting on the deployment of digital systems for both powder material expertise and control of process and component capabilities. The advanced digital systems, developed to support AM deployment, were identified as InstAMetal (a 'virtual storefront' to provide a customer focus) and ADDvantage (a 'shop floor of the future', involving the management of AM in multiple plants with central intelligence). Dr Höges concluded that the developed partnerships were driving technology progress, but that challenges still lay ahead, in material variety, development of enhanced design know-how, process robustness, automation of depowdering, realising full productivity potential and the full deployment of digital workflows.

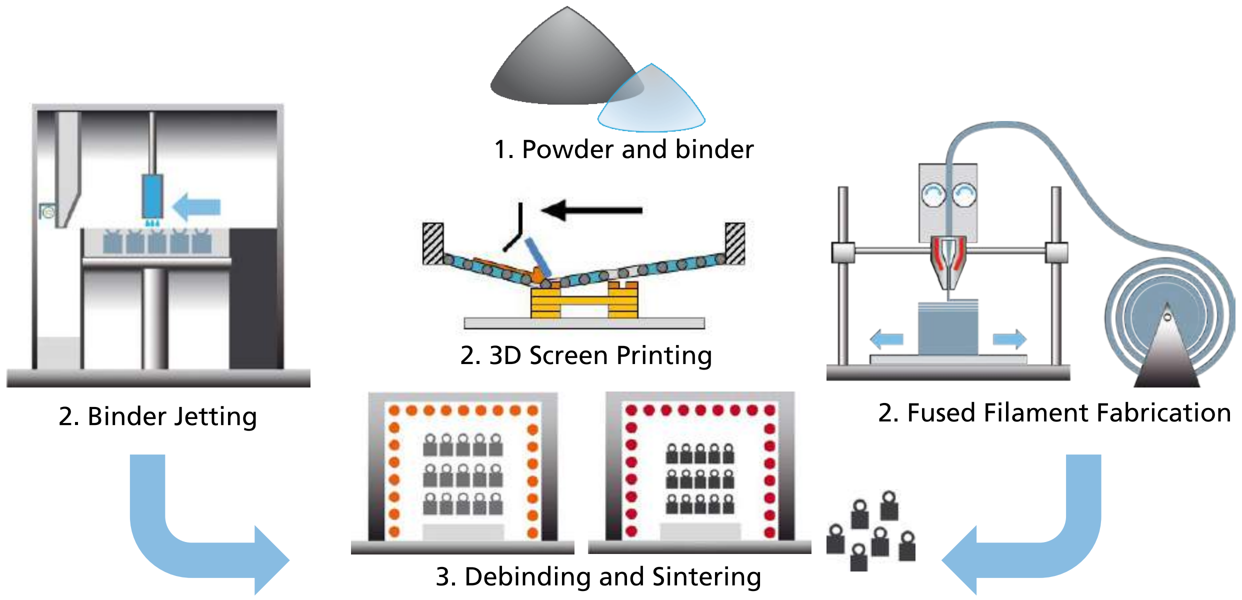


Fig. 9 Sinter-based AM technology process expertise at Fraunhofer IFAM

MIM and the chances of AM processes

The final presentation in the seminar came from Dr Thomas Hartwig, Fraunhofer IFAM, Germany, who considered the ways in which the growing adoption of AM might provide both direct and indirect benefits to the future growth of MIM. In stating IFAM's credentials in this field, Dr Hartwig pointed to the institute's forty years of experience in sintering processes, thirty years of experience in MIM technologies and twenty-five years of experience in AM - initially in rapid prototyping.

He then provided an overview of existing AM technologies, paying particular attention to sinter-based processes - Binder Jetting, Fused Filament Fabrication and 3D Screen Printing (Fig. 9).

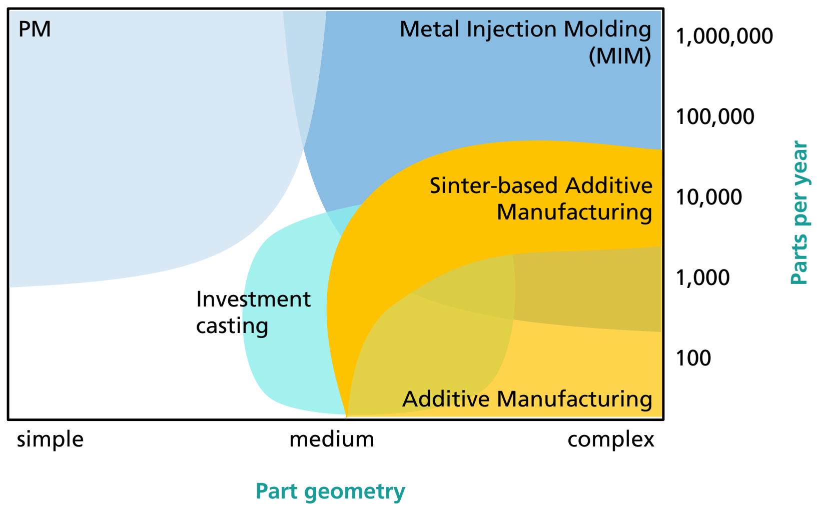


Fig. 10 Potential market penetration for binder-based AM (vs MIM, Investment Casting and other AM technologies)

For these sinter-based AM technologies, predictions were offered as to what the future might hold and four future trends were suggested.

The first proposed trend was that these sinter-based technologies will capture a substantial market share in AM. This growth in potential markets, in applications of medium to high geometrical complexity, will be at the expense of other AM technologies and investment casting, but, for annual production volumes up to around 50,000 parts, also of MIM (Fig. 10). It was also predicted that the growth of markets for AM technologies in general would be enabled by reductions in part costs of around 50% over the decade 2013–2023 and a 400% increase in production rates over the same period (Fig. 11).

The second trend discussed was the predicted increase in the variety of materials available as feedstocks for sinter-based AM processes. Table 2 shows the material types already available or under development for Binder Jetting and Fused Filament Fabrication. The use of either process for the manufacture of aluminium parts was, however, rated as inherently difficult.

A third trend was predicted to be a significant reduction in scrap rates. In this context, it was noted that any defects introduced during shaping cannot be healed by the debinding and sintering steps and that, therefore, all parameters in the whole process chain need to be under control.

The search for enhanced process robustness and higher productivity will include the development of finer and cheaper powders, the development of stronger binders for larger and more complex shapes, the elimination of the drying/hardening step, the development of faster and more precise builds with more effective powder removal, the increased use of sintering process simulation to predict shrinkage and warpage, and enhanced analysis techniques for the effects of sintering atmospheres.

Echoing the comments of the previous presenter, the benefits of adopting digital in-line quality surveillance were highlighted. This would aid in improving green part quality by monitoring and documenting changes in the production process, thus enabling long-term analyses and statistical evaluations. Safeguarding process quality would involve providing early warnings of approaching quality deviations, thus allowing fast and timely intervention without process interruptions.

Areas where digital tools can assist were highlighted as process control (printing reproducibility, prediction of shrinkage and warpage and sintering simulation) and design (through the use of design recommendation and material behaviour libraries). Professional simulation tools are already available for MIM and for L-PBF AM (Fig. 13); for binder-based AM, the relevant applications are still to be developed.

A final predicted trend would involve a shift in supplier structure. It was proposed that future supply chains for binder-based AM would be populated by specialist companies: powders would be bought from specialist powder manufacturers, binders would be bought from system manufacturers ('printer cartridges') and feedstock would be provided by filament producers. In relation to AM part production, this author felt that, on balance, this space would probably be more properly filled by established PM/

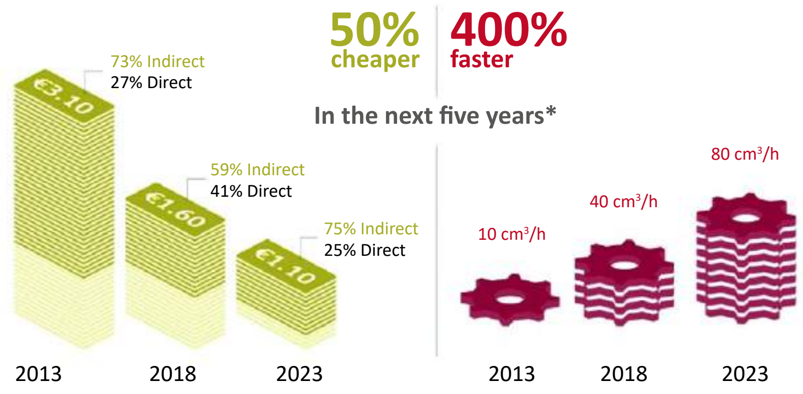


Fig. 11 Future developments in cheaper, faster AM (Courtesy Siemens AG)

	Binder Jetting	Fused Filament
Stainless steels	✱	✱
Tool steels	✱	✱
Superalloys	✱	✱
Titanium	✱	✱
Aluminium	✱	✱
Copper / Bronze	✱	✱
Carbides	✱	✱
✱ Available ✱ Under development ✱ Inherently difficult		

Table 2 Material types for binder-based AM technologies

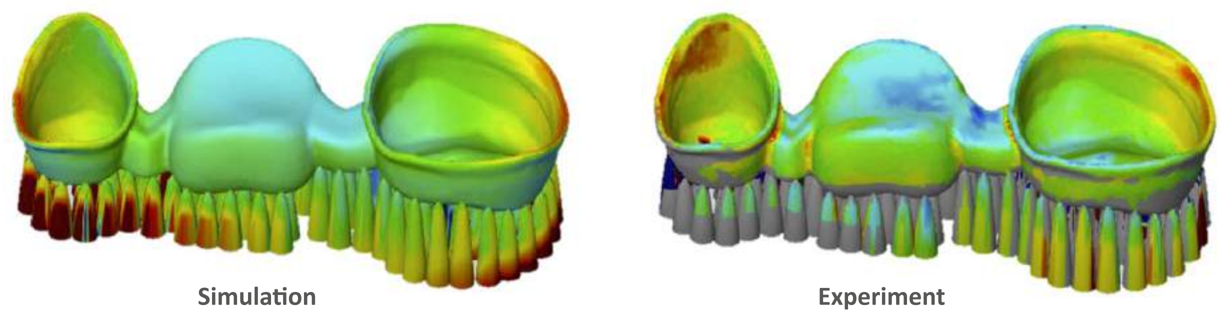


Fig. 12 L-PBF simulation and experiment for a dental prosthesis (Courtesy ISEMP / Bego Medical)

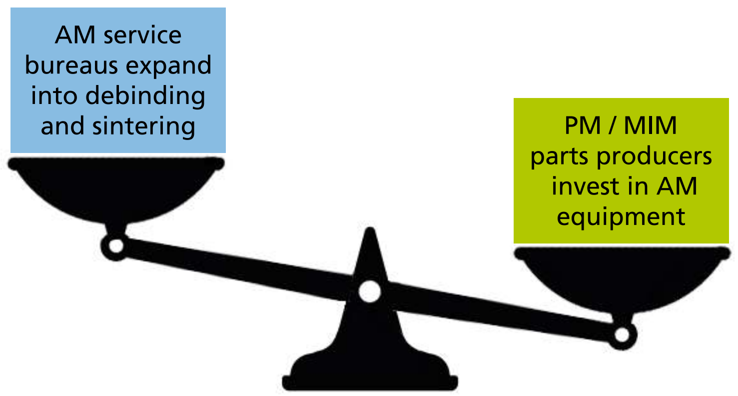


Fig. 13 The future of binder-based AM part production?

MIM producers investing in AM equipment, rather than AM service bureaus expanding into debinding and sintering (Fig. 13).

Conclusion

It was concluded that MIM could benefit directly from the use of AM technology in toolmaking, e.g. providing a route to shorter lead time, cheaper tooling, allowing the incorporation of conformal cooling channels (reducing injection process times) or allowing the manufacture of lost cores (to extend markets into hollow MIM products).

Also, a number of potential indirect benefits for MIM from AM were highlighted. Firstly, the growth of AM will enhance the market acceptance of powder-based materials. The MIM industry has long included, in its list of impediments to market penetration, the general lack of awareness of the technology amongst product designers in potential customer organisations.

In view of its rapidly established high profile, this impediment seems not to exist for AM and there could well be an opportunity for MIM to take advantage of this situation to raise its own profile. Other indirect benefits to MIM from increasing adoption of AM may include a possible lowering of powder costs and the increased impetus for the development of a wider range of feedstock materials, of enhanced process control tools and of digitalisation methodologies.

Author

Dr David Whittaker
Tel: +44 1902 338498
whittakerd4@gmail.com

The MIM of Nimonic 90 for a new generation of turbocharger components

Nimonic 90, a trademarked superalloy produced by Special Metals Corporation, is designed specifically for high-temperature applications. Primarily, it is used in turbine blades, discs, ring sections, and forging and hot working tools. When processed by MIM, Nimonic 90 has the potential for superior mechanical properties which could pave the way for the use of Metal Injection Moulding in new automotive applications such as turbocharger compressor wheels. Here, Boon Sing Ng, Alvin Wei Yang Lim and Chee Hoo Liang, from Singapore's AMT Pte Ltd, look at the material's economic and functional viability, when compared to conventional alloys such as aluminium, as the material for the next generation of high-performance MIM applications.

Nimonic 90 was developed by Special Metals Corporation, headquartered in New Hartford, New York, USA, a subsidiary of Precision Castparts Corp. The wrought, nickel-chromium-cobalt base alloy is strengthened with additions of titanium and aluminium, and was designed specifically for service at high temperatures of up to 920°C, such as in turbine blades, discs, forgings, ring sections and hot working tools [1]. Nimonic 90 can be processed stably and reliably via MIM [2], and the superior mechanical properties expected to be shown by MIM Nimonic 90 at high temperatures may open new opportunities for applications in the automotive industry, notably in turbochargers. Due to the rising need for compressor wheels to operate with higher percentages of exhaust gas recirculation, which means higher inlet temperature and a more corrosive environment, increased demands are being placed on the mechanical properties of conventional aluminium alloy-based compressor wheels [3]. MIM Nimonic 90 seems to be functionally and economically viable in rivalling aluminium alloy as the material for the next generation of turbocharger compressor wheels.

Development of Nimonic 90

The development of superalloys began in the early twentieth century [4]. With the increase in demand for improved high temperature alloys in aircraft gas turbines, the first Nimonic

Fig. 1 AMT Pte Ltd's 4000 m² plant in Tuas Lane. AMT is the contract manufacturing arm of Advanced MedTech Holdings, a wholly-owned subsidiary of Temasek Holdings, an investment company headquartered in Singapore.

Element	Composition % (Mill cert)	Specification from Special Metals Corporation
C	0.004	Max 0.13
Si	1.04	Max 1.0
Mn	0.03	Max 1.0
Cr	19.04	18-21
Fe	0.28	Max 1.5
Co	19.11	15-21
Al	1.49	1-2
Ti	2.57	2-3
B	0.00	Max 0.02
Zr	0.01	Max 0.15
O (ppm)	2900	-
Ni	Balance	

Table 1 Chemical composition of Nimonic 90 powder

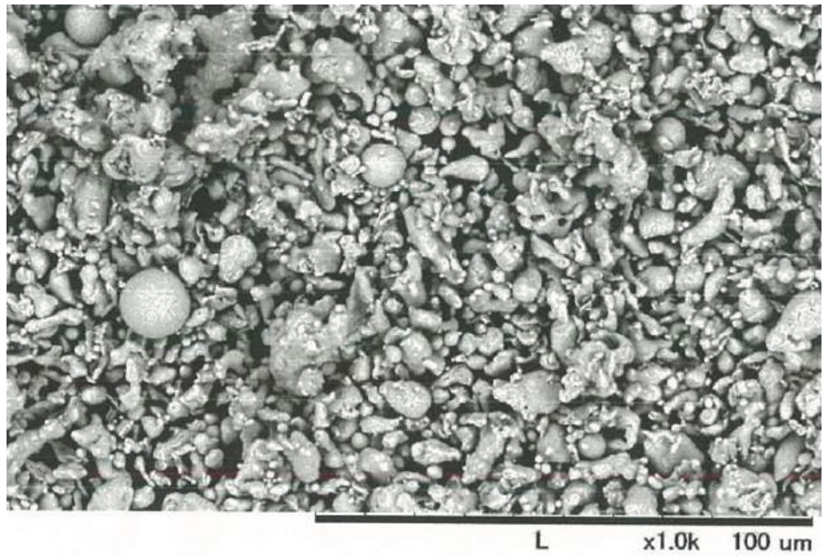


Fig. 2 Micrograph of Nimonic 90 powder

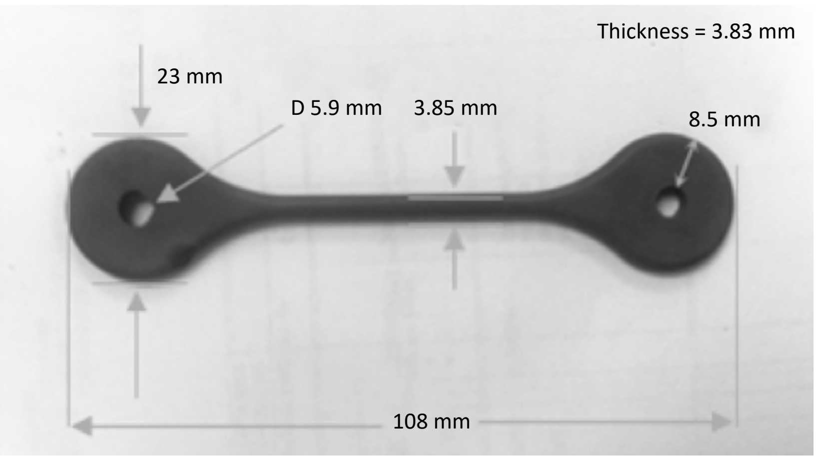


Fig. 3 Green Nimonic 90 tensile specimen

alloy – Nimonic 80 – was developed in 1941 by Leonard Bessember Pfeil at Inco's Wiggin factory in the UK.

The alloy was derived from Nichrome V by adding 0.3% titanium and 0.1% carbon. Nimonic 90 followed in 1945, offering higher temperature resistance due to the further addition of cobalt [5]. Nickel-based superalloys in general are considered 'super' due to the existence of gamma prime (γ') phase [6], an intermetallic compound (Ni_3Al) which precipitate strengthens the gamma (γ) phase (Ni). Increased temperature gives rise to the strength of γ'. Carbides in form of MC, $M_{23}C_6$ and M_6C are also phases of importance in strengthening the matrix. Co, Fe, Cr are the major matrix-class elements which contribute to solid-solution strengthening of γ phase [7].

This study focuses primarily on the development of Nimonic 90 parts by Metal Injection Moulding, looking at the optimisation of both the sintering and heat treatment profiles to determine their effects on mechanical and microstructural properties. Tensile and creep properties were tested, while microstructural analysis was carried out using optical light microscopy and scanning electron microscopy.

Method

MIM processing

The MIM processes involved were mixing, moulding, solvent debinding, thermal debinding and sintering. Water-atomised Nimonic 90 powder supplied by Epson Atmix Corporation, Japan, was mixed with a proprietary wax-based binder system developed in-house by AMT. The chemical composition of Nimonic 90 powder is shown in Table 1. The particle size distribution of the powder was analysed using a Mastersizer 3000, and found to fall into the range of D10 = 3.4 µm, D50 = 8.2 µm and D90 = 18.8 µm. As shown in Fig. 2, the Nimonic 90 powder used in this study is irregular shaped. The powder and binders, with a volumetric ratio of 3:2,

Sintering combination	Sintering peak temperature (°C)	Sintering pressure	Environment at peak sintering temperature	Protection
S1	1280	3.5 - 4 psig	Nitrogen	Without shield
S2	1280	20 mTorr	Vacuum	Without shield
S3	1280	20 mTorr	Vacuum	With TZM molybdenum alloy shield

Table 2 Sintering conditions of MIM Nimonic 90

were mixed in 5 litre planetary mixer at 160°C for 3 hours at atmospheric pressure and it was further extended for 1 hour in ambient vacuum (~ -1 bar).

After mixing, molten feedstock was cooled to room temperature and consequently crushed into granulate form. Specimens in the shape of tensile bar (Fig. 3) [8] were moulded using Arburg Allrounder 420C injection machine. The moulding process was carried out according to the following parameters: pressure 500 bar, flow rate 30 cm^3/s, barrel temperature 155°C and mould temperature 55°C.

Green Nimonic 90 tensile specimens were debound through solvent and thermal debinding. During the solvent debinding stage, tensile specimens were soaked in an organic solvent at 55°C for 12 hours. This was followed by thermal debinding at 650°C with 40 L/min nitrogen supply.

Debound tensile specimens were sintered in a graphite furnace at 1280°C for 3 hours. Sintering at different pressures and in different environments was investigated (Table 2). During the sintering process, TZM molybdenum alloy shield as shown in Fig. 4 was used to mitigate any surface contamination of the tensile specimens.

Fig. 4 TZM molybdenum shield

Dimensional analysis

Five tensile specimens of differing dimensions, at both the green and sintered stages, were measured using vernier caliper.

Heat treatment

The optimised sintered tensile specimens were heat treated with a standard profile [1]. The standard heat treatment profile comprised two phases, with the first phase being solution treatment (hold at 1080°C for 8 hours, then air cool) and the second phase being age hardening (hold at 700°C for 16 hours, then air cool). The solution treatment temperature is higher than the γ' solvus temperature and hence dissolves γ' and possibly carbides. This is followed by recrystallisation and grain growth to a desired size. Age hardening precipitates γ' homogeneously, as well as carbide at grain boundaries [2]. Two third phase heat treatment profiles [9] were introduced to improve ductility. The heat treatment profiles are summarised in Table 3.

Tensile test

Tensile tests were carried out at room temperature, referring to ASTM E8/E8M-13a 'Standard Test Method for Tension Testing of Metallic Materials'.

	Heat treatment profiles
H1	Hold at 1080°C for 8 hours, then air cool (first phase); hold at 700°C for 16 hours, then air cool (second phase) – Standard heat treatment profile for Nimonic 90 [1]
H2	Standard heat treatment profile; hold at 950°C for 5 mins (third phase) [9]
H3	Standard heat treatment profile; hold at 925°C for 1 hour (third phase) [9]

Table 3 Heat treatment profiles for MIM Nimonic 90

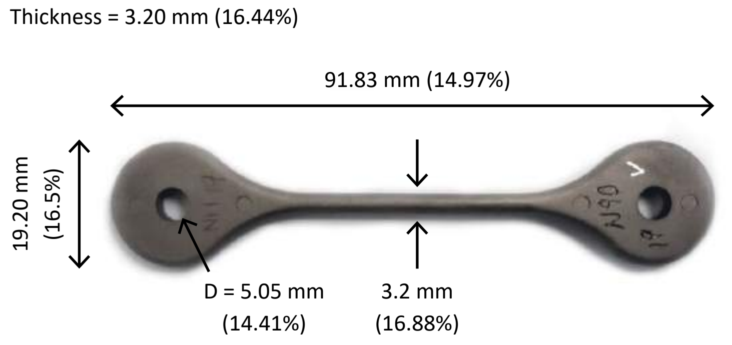


Fig. 5 Dimension and shrinkage percentage of the tensile specimens

Condition	UTS (MPa)	YS* (MPa)	Elongation (%)	Reduction area (%)
S1	229	187	0.9	2.8
S2	958	691	2.0	4.7
S3	1100	705	19	13
* Yield strength was determined by 0.2% offset method				

Table 4 Tensile results for sintered MIM Nimonic 90

Heat treatment profile	UTS (MPa)	YS* (MPa)	Elongation (%)	Reduction area (%)
H1	1155	872	12	6
H2	1035	719	20	-
H3	978	622	26	-
* Yield strength was determined by 0.2% offset method				

Table 5 Tensile results of heat treated MIM Nimonic 90

	UTS (MPa)	YS* (MPa)	Elongation (%)
Nimonic 90 in form of extruded bar (heat treated via H1 profile)	1175	752	30
* Yield strength was determined by 0.2% offset method			

Table 6 Tensile properties of Nimonic 90 extruded bar [1]

Creep testing

Creep testing was carried out on the optimised heat treated tensile specimen. The tensile specimen was mounted onto the fixture of the universal testing machine. and ramped to 550 MPa at 50 Ns^{-1}. It was then held for 100 hours at 300°C.

Micrographical analysis

Sintered and heat treated tensile specimens were cross sectioned, ground and polished before they were micrographically analysed under optical light microscope and Scanning Electron Microscope (SEM). The specimens were analysed for their grain size and porosity.

Results and discussion

Dimensional study

Fig. 5 shows the dimension and shrinkage percentage of the sintered part under S3 sintering conditions. Processing under a vacuum environment, the range of shrinkage was quite wide, with shrinkage percentages falling between 14.41% and 16.88%. The wide range of shrinkage factor was mainly due to shape distortion and warping issues at certain dimensions.

Tensile test – Sintered MIM Nimonic 90

The tensile results are shown in Table 4. Overall, Nimonic 90 is unsuitable for sintering under a nitrogen atmosphere (S1) as tensile results indicated poor strength and ductility. The mechanical properties of Nimonic 90 can only be retained under vacuum sintering (S2 and S3). A significant rise in the tensile properties was seen in S2 and S3, with ultimate tensile strength and yield strength showing readings of around 1000 MPa and 700 MPa respectively. By using a TZM molybdenum alloy shield (S3), the issue of surface contamination was resolved. Moreover, it was shown that ductility can be further improved (reaching 19%) using the TZM molybdenum alloy shield, without sacrificing the material's tensile properties,

Tensile test – Heat treated MIM Nimonic 90

Tensile specimens sintered under the S3 sintering conditions, which showed the optimum mechanical properties in the study, were heat treated with the different profiles shown in Table 3. The tensile results of the heat treated tensile specimens from S3 are summarised in Table 5. After treatment using the H1 profile, yield strength was slightly raised from 700 MPa to 800 MPa, while ultimate tensile strength showed a slight increase (not more than 100 MPa) compared to the as-sintered Nimonic 90. An adverse effect was observed on the ductility of the specimen, which decreased from 19% to 12%.

The third phase of heat treatment profiles (H2 or H3) were proven to recover the ductility substantially, with a slight sacrifice of strength.

Overall, the strength of MIM Nimonic 90 was comparable to Nimonic 90 extruded bar (Table 6). However, due to the absence of pores in the extruded bar, the ductility of the extruded Nimonic 90 was much superior compared to MIM Nimonic 90.

Creep testing

The creep test setup is shown in Fig. 6. The heat treated tensile coupon (S3 sintering condition and H1 heat treatment profile) was held for 100 hours at 550 MPa and 300°C (Fig. 7). As 550 MPa was exerted on the tensile specimen, the displacement gauge showed elongation at 2.2 mm initially. Elongation remained stagnant until the end of the test. MIM Nimonic 90 survived the creep cycle of 550 MPa at 300°C for 100 hours.

Micrographical analysis – Porosity

The micrograph of the unetched MIM Nimonic 90 (S3) is shown in Fig. 8. The porosity level of the sintered Nimonic 90 (S3) achieved A08 [10].

Micrographical analysis – Etched condition

Micrographs of the etched MIM Nimonic 90 at sintered (S3) and heat treated (H1, H2 and H3) conditions

Fig. 6 Creep test setup

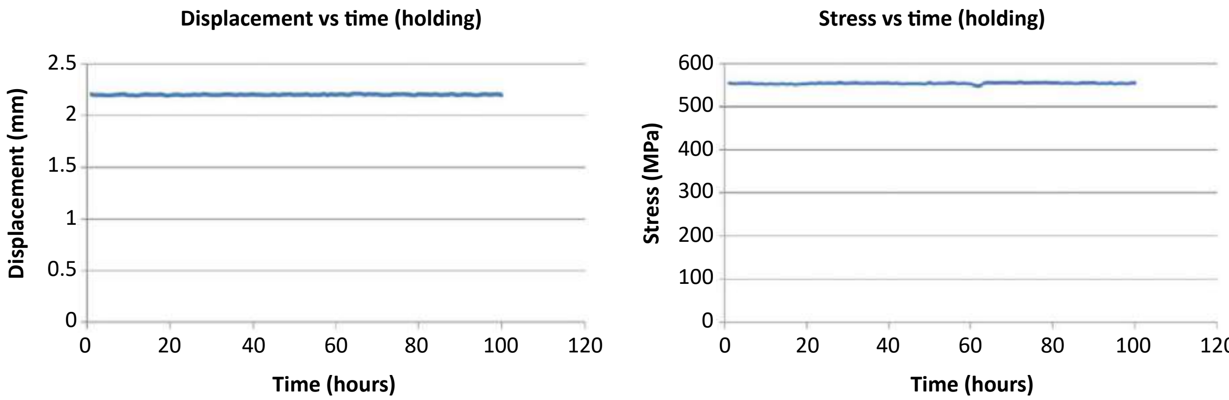


Fig. 7 Creep test results. (a) Displacement vs time (holding) and (b) Stress vs time (holding)

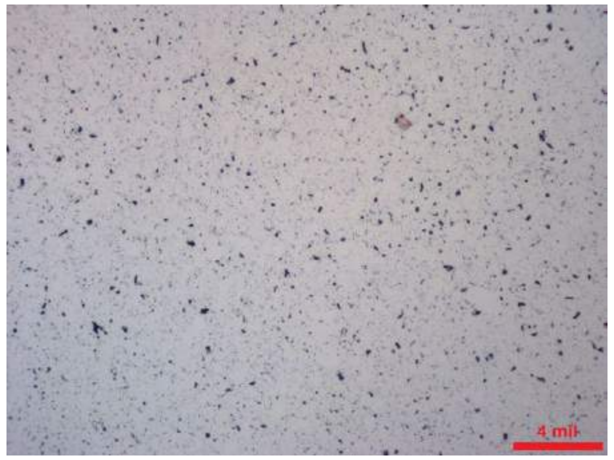


Fig. 8 Micrograph of the unetched MIM Nimonic 90 (S3 sintering condition)

were observed under optical light microscope (Fig. 9). In terms of grain size, the structure shown in the micrographs is finer than ASTM 8 (22.4 µm). Bright dots can be seen along the grain boundaries and these are believed to be the metal carbide (either in the form of chromium carbide or titanium carbide) [2]. As seen in Fig. 9b, the H1 heat treatment profile triggered the formation of metal carbides and localised them along the grain boundaries. Relocation of metal carbides on the grain boundaries enhanced the overall strength of the matrix. γ' phase (Ni_3Al) for this material is expected to form at the outer layer of metal carbide as well inside the main matrix [2]. Therefore, the specimen heat treated with H1 was expected to acquire a higher volume ratio of γ' phase along the grain boundary region. However, the elongation was reduced as a result of strengthening. As the third phase heat treatment profile was added into the standard heat treatment profile (H1), metal carbides were restructured into a smaller size (Fig. 9d). The size of the metal carbide became even smaller as the modified heat treatment temperature increased (Fig. 9c).

In order to understand the nature of the precipitates, the etched surface of MIM Nimonic 90 was observed using SEM. Fig. 10 shows SEM micrographs of etched MIM Nimonic 90 at sintered (S3) and heat treated (H1, H2 and H3) conditions. For as-sintered MIM Nimonic 90 (S3), metal carbides were seen segregating either intergranularly or intragranularly (Fig. 10a). After going through the standard heat treatment profile (H1),

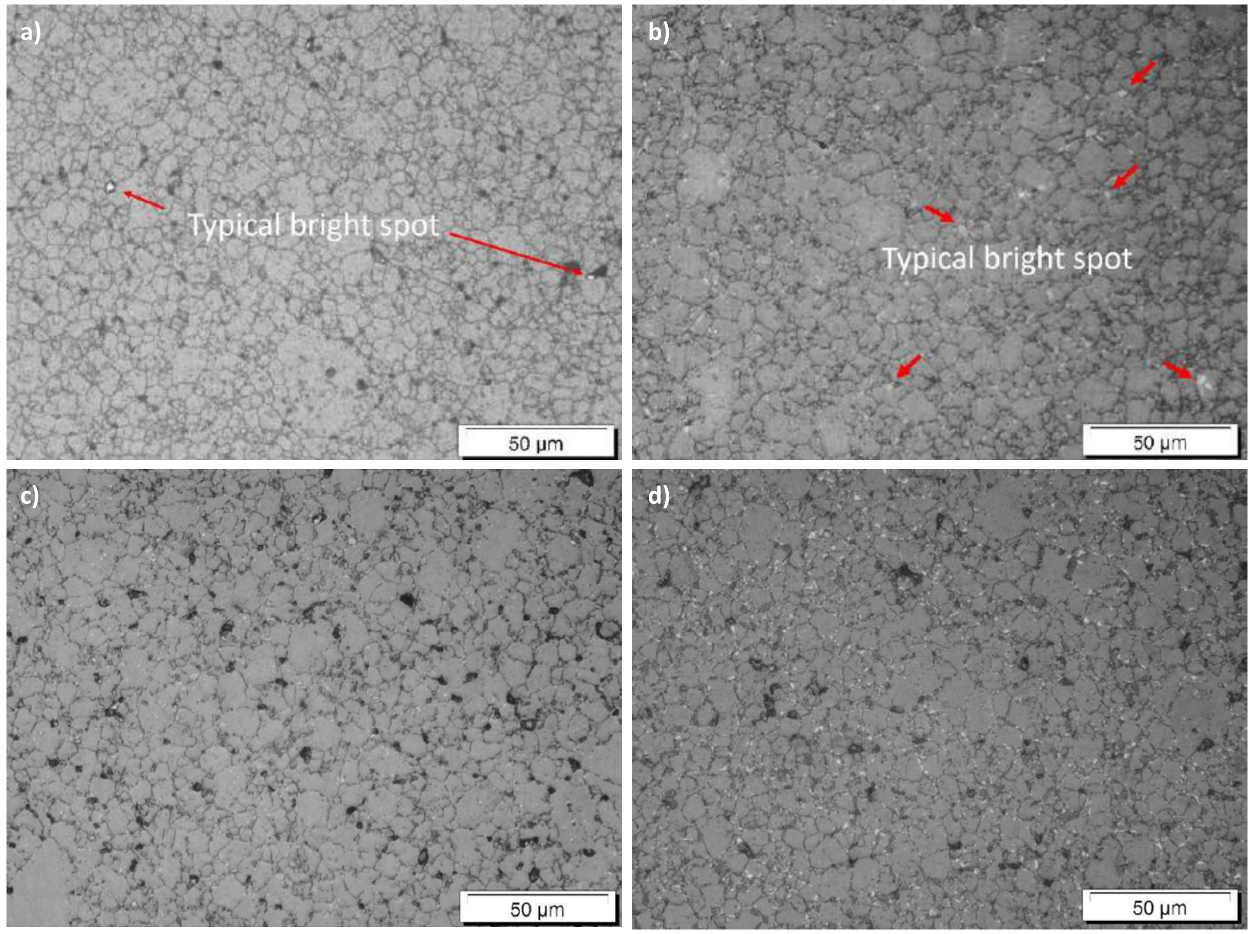


Fig. 9 Micrograph of etched MIM Nimonic 90 with respective sintering condition and heat treatment profiles: (a) S3, (b) S3+H1 (c) S3+H2 and (d) S3+H3

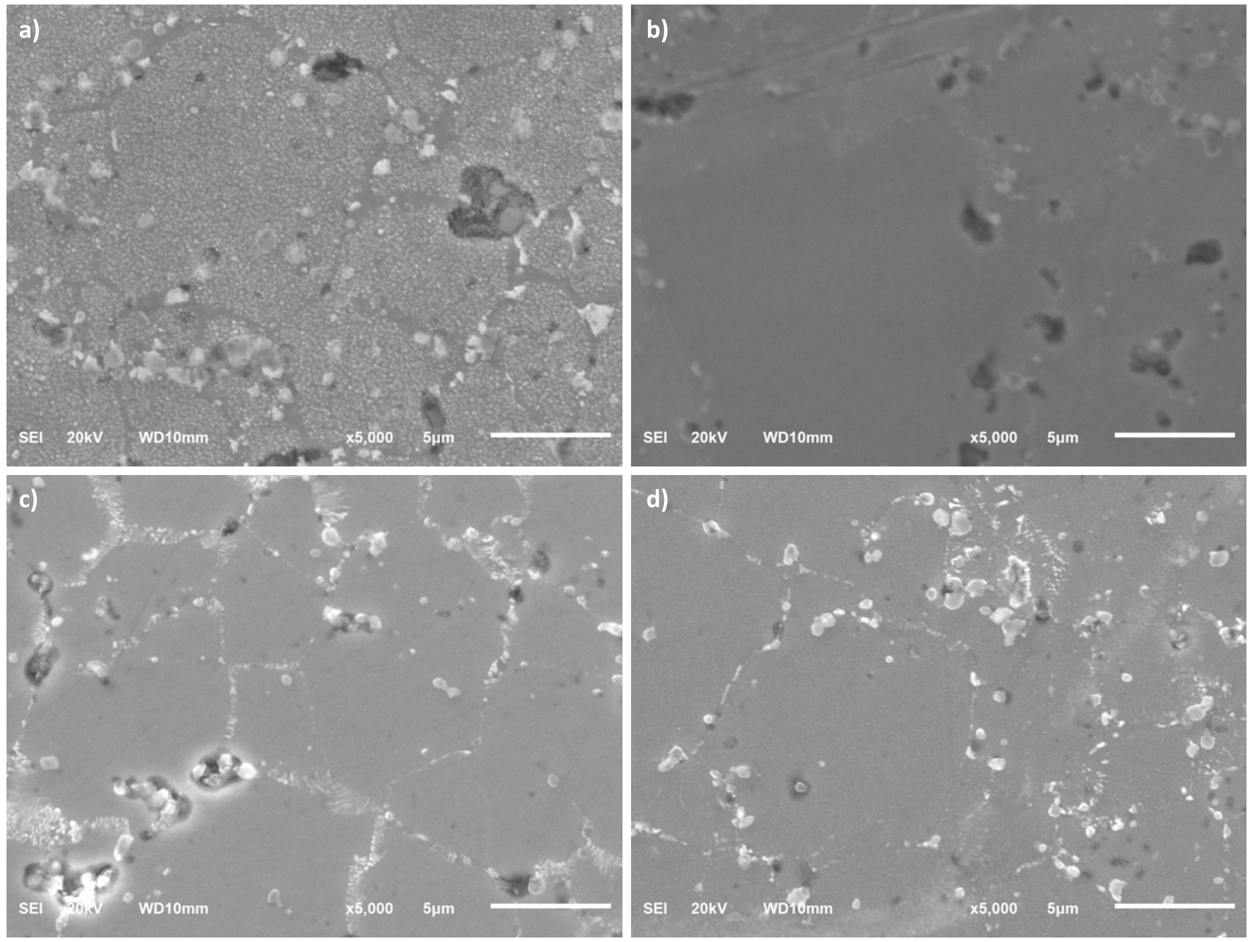


Fig. 10 SEM micrograph of etched MIM Nimonic 90 with respective sintering condition and heat treatment profiles: (a) S3, (b) S3+H1, (c) S3+H2 and (d) S3+H3

metal carbides were dissolved and relocated along the grain boundaries (Fig. 10b). In line with tensile testing results, the strength of the matrix was enhanced while a drop in ductility was believed to be caused by the continuously connected carbide form. The occurrence of the carbide phase apparently reinforced the hardening effect of the γ' phase, resulting in high creep resistance, but low ductility and low rupture life [9]. The phenomenon of carbide restructuring in H2 and H3 treated MIM Nimonic 90 as seen under optical light microscope (Figs. 9c and d) was further confirmed under SEM observation (Figs. 10c and d). A lower volume ratio of carbide was seen in H2 and H3 treated specimens compared to H1 treated MIM Nimonic 90. H2 and H3 heat treatment profiles, which were set at 925–950°C, seemed to dissolve the carbide partially and caused the strength reduction which was observed in the tensile results (Table 5). The restructuring of carbide to nodular discontinuous form along the grain boundaries as spotted in Figs. 10c and d was believed to give rise to the ductility, with a slight decrease in strength.

Conclusion

MIM Nimonic 90 demonstrated room temperature mechanical properties comparable to Nimonic 90 extruded bar produced by Special Metals. It survived the creep test of 550 MPa at 300°C for 100 hours. The ductility of the H1 treated MIM Nimonic 90 can be recovered by using the third phase of heat treatment profiles (H2 and H3), but this leads to a marginal loss of strength properties. The occurrence of discontinuous carbide (nodular form) along the grain boundaries is believed to enhance ductility.

Contact

Liang Chee Hoo
Director of Business Development & Technology
AMT Pte Ltd
3 Tuas Lane
Singapore 638612

liangch@amt-mat.com
www.amt-mat.com

References

[1] Special Metals. (2004). *Nimonic 90 alloy. 90*

[2] Özgün, Ö., Gülsoy, H. Ö., Findik, F., & Yilmaz, R. (2012). 'Microstructure and mechanical properties of injection moulded Nimonic-90 superalloy parts', *Powder Metallurgy*, 55 (5), 405–414. https://doi.org/10.1179/1743290112Y.0000000010

[3] Turbochargers: How They Work, and Current Turbo Technology, by EPI Inc. (n.d.). Retrieved September 15, 2019, from http://www.epi-eng.com/piston_engine_technology/turbocharger_technology.htm

[4] Sims, C. T. (2012). *A History of Superalloy Metallurgy for Superalloy Metallurgists.* 399–419. https://doi.org/10.7449/1984/superalloys_1984_399_419

[5] Gessinger, G. H. (1984). *Powder Metallurgy of Superalloys.* https://doi.org/10.1016/C2013-0-06291-3

[6] Torralba, J. M. (n.d.). *High Temperature Materials*

[7] Reed, R. C. (2006). *The Superalloys.* https://doi.org/10.1017/CBO9780511541285

[8] ASTM Standard E8/E8M-13a. (2013). 'Standard Test Methods for Tension Testing of Metallic Materials.' In ASTM International. https://doi.org/10.1520/E0008_E0008M-13A

[9] D M Dovey. (1963). Heat treatment of metals. Lectures delivered at the Institution of Metallurgists refresher course, 1962. In *London, Iliffe.*

[10] Technical Committee ISO/TC 119 "Powder metallurgy" (2016). *BSI Standards Publication Hardmetals — Metallographic determination of microstructure Part 4: Characterisation of porosity , carbon defects and eta-phase content.* Retrieved from https://www.iso.org/standard/61266.html

industry events

2020

PM20
February 19-21, Mumbai, India
www.pmai.in/pm20

Asiamold 2020 / 3D Printing Asia Zone
February 26-28, Guangzhou, China
http://asiamold-china.cn.messefrankfurt.com/guangzhou/en.html

MIM2020
March 2-4, Irvine, United States
www.mim2020.org

EPMA Hot Isostatic Pressing Seminar
March 10-11, Oslo, Norway
http://seminars.epma.com/hip-2020/home

METAV 2020
March 10-13, Düsseldorf, Germany
www.metav.com

4th Additive Manufacturing Forum Berlin 2020
March 11-12, Berlin, Germany
www.additivemanufacturingforum.com

PM China 2020
March 24-26, Shanghai, China
en.pmexchina.com

Rapid + TCT 2020
April 20-23, Anaheim, United States
www.rapid3devent.com

Ceramics Expo 2020
May 5-6, Cleveland, United States
www.ceramicsexpousa.com

WorldPM2020
June 27 - July 1, Montréal, Canada
www.worldpm2020.org

PMCC&AC Expo 2020
July 1-3, Shenzhen Shi, China
www.pmccexpo.com

PM Life - Additive Manufacturing Module
August 24-28, Dresden, Germany
www.pmlifetraining.com/about/additive-manufacturing

Formnext + PM South China
September 9-11, Shenzhen Shi, China
www.formnext-pm.hk.messefrankfurt.com/shenzhen/en.html

Euro PM2020
October 4-7, Lisbon, Portugal
www.europm2020.com

Event listings and media partners

If you would like to see your PIM/MIM/CIM-related event listed in this magazine and on our websites, please contact Nick Williams, email: nick@inovar-communications.com.

We welcome enquiries regarding media partnerships and are always interested to discuss opportunities to cooperate with event organisers and associations worldwide.

advertisers' index