

FOR THE METAL, CERAMIC AND CARBIDE INJECTION MOULDING INDUSTRIES

Vol. 12 No. 4 DECEMBER 2018

# POWDER INJECTION MOULDING

**INTERNATIONAL**



**in this issue**

**MIM, CIM & Additive Manufacturing  
World MIM status update  
Euro PM2018 technical report**



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## 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.

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## Printed by

Cambrian Printers, Aberystwyth, United Kingdom  
ISSN 1753-1497 (print)  
ISSN 2055-6667 (online)  
Vol. 12. No. 4 December 2018  
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For the metal, ceramic and carbide injection moulding industries

## Positive global trends for the PIM industry?

For the global PIM industry, 2018 appears to have been a year of positive growth. With a lack of hard data, however, the true picture of progress in MIM and CIM is becoming increasingly hard to come by. In both Europe and North America the industry has, to a large extent, relied on annual surveys of sentiment; whilst such surveys give some degree of insight, the complete picture is compromised by limited participation and a lack of raw data.

Although regional trade associations would jump at the chance to assess full production data from part makers and materials suppliers, the reality is that within the competitive environment of PIM, this is now almost impossible to achieve. What we are left with is a fragmented view of trends in the PIM industry, sometimes with heavily contrasting estimates of sales values, tonnages, growth and the outlook for the industry.

As a result, the performances of powder, feedstock and equipment suppliers have for some time been used as a barometer for the health of the industry. Now, however, with the rapid growth of metal AM, even these indicators can lead to confusion. MIM furnace makers and powder suppliers are busy and are looking to invest in increased capacity, but to what extent will this be driven by MIM-like metal AM processes, rather than growth in MIM itself?

Japan is, of course, the exception, and the latest data, published on [page 8](#) of this issue, shows growth in 2017 and a forecast that this will continue in the near future.

Nick Williams,  
Managing Director & Editor



## Cover image

A Fused Filament Fabrication (FFF) machine with components made from SiC/SiC filaments (Courtesy Fraunhofer IKTS)



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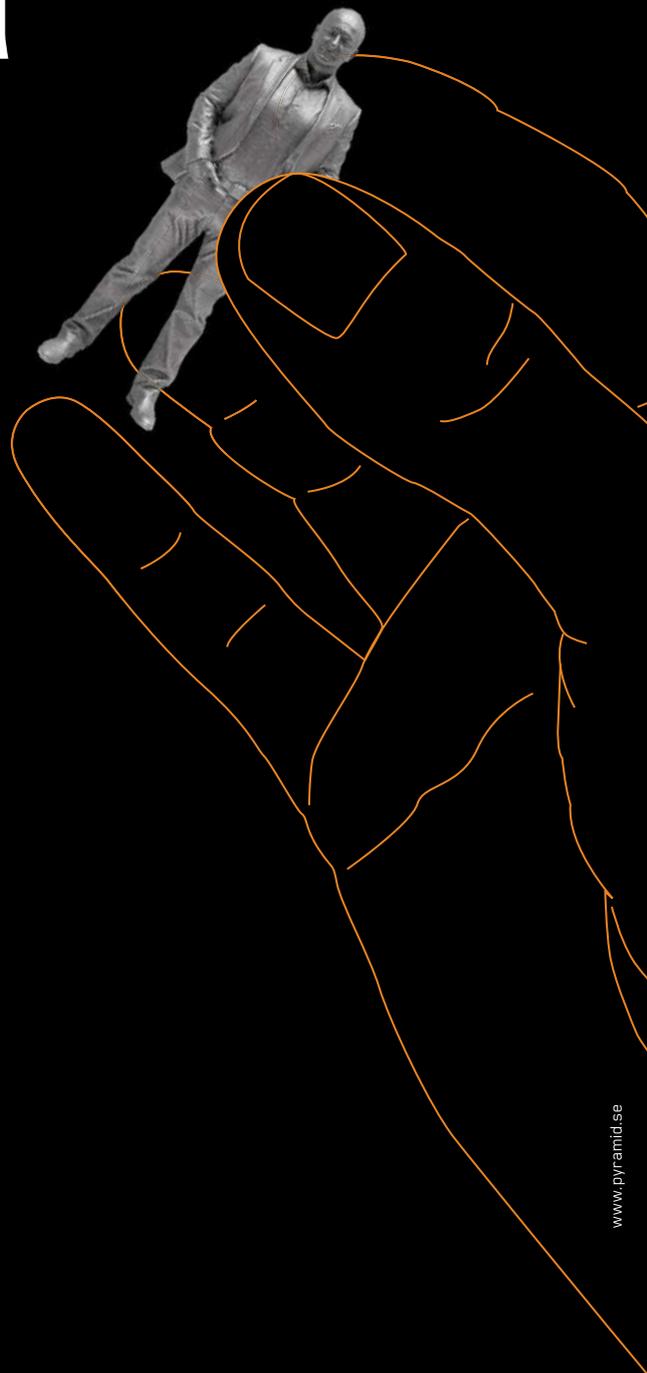
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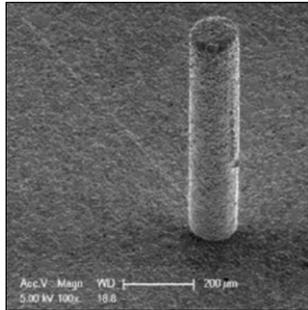


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## In this issue

### 57 Threat or opportunity? The MIM industry as a partner, a target and a market for metal AM

In September, HP announced its entry into the world of metal Additive Manufacturing with the launch of a new binder-based AM system, the HP Metal Jet. The fact that HP's launch partners, Parmatech and GKN Powder Metallurgy, are well-known MIM producers serves to highlight just how close the worlds of AM and MIM have become; a fact evidenced by multiple launches and developments over the past few years. In this report, Nick Williams reviews the attraction of AM for MIM producers, and the equally strong attraction of MIM for AM machine builders.

### 67 WORLDPM2018: Global MIM markets show healthy growth

The WORLDPM2018 Congress & Exhibition, Beijing, China, highlighted not only the rapid industrial growth that has been achieved in the country over the past two decades, but also the many advances made in PM materials and production technology. This applies equally to Metal Injection Moulding, which has been enjoying high growth in China as well as in other regions around the world. Bernard Williams summarises the global status of MIM as well as production and technology trends based on key presentations during WORLDPM2018's Plenary and Special Interest Sessions.

### 77 Ceramic Injection Moulding and Ceramic Additive Manufacturing side by side: Opportunities and challenges

The arrival of production-ready 'MIM-like' metal AM technologies is today opening up a new world of opportunities for MIM producers. As Tassilo Moritz and colleagues from the Fraunhofer Institute for Ceramic Technologies and Systems (IKTS) explain, the same opportunities will soon also be open to CIM producers. In this article, two ceramic AM processes, both based on CIM-like thermoplastic feedstocks, are reviewed and the opportunities and challenges of the processes examined.

### 87 Euro PM2018: Innovations in MIM highlighted in Bilbao

A number of technical papers presented at Euro PM2018, Bilbao, Spain, October 14-18, 2018, addressed processing and compositional developments in Metal Injection Moulding. In this report, Dr David Whittaker reviews four papers that cover Lost-Form PIM, an innovative debinding and sintering process, the MIM of Ti-6Al-4V HDH powder with the addition of yttrium, and the use of iron as a low-cost sintering aid for Ti-6Al-7Nb.

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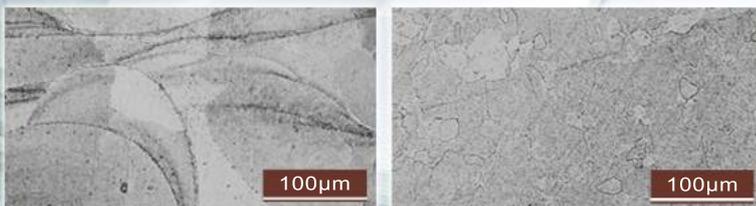
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# Industry News

## Tekna opens expanded metal powder production facility

Metal powder manufacturer Tekna Plasma Systems Inc., Sherbrooke, Quebec, Canada, has expanded its second plant and implemented a new manufacturing infrastructure. The result of a \$5.5 million investment by the company, the expansion has doubled the size of its metal powder production facilities.

The additional space created will reportedly be used for the immediate and future deployment of new metal powder production units, the introduction of new research infrastructure and the relocation of part of its administrative staff. Rémy Pontone, Tekna's Vice President, Sales and Marketing, stated, "This investment will enable us to follow and support the growth of our clients through our existing products and to launch

new innovative products on the industrial market." Luc Dionne, Tekna CEO, added, "This expansion, which is part of our five-year growth plan, will increase our annual metal powder production capacity to over 1,000 tonnes. Our world-class manufacturing infrastructure and our accreditations in terms of the strictest quality standards make Tekna a reliable partner that our clients can count on to ensure their current and future success."

Tekna manufactures metal powders for MIM, AM, HIP and thermal spray, including Ti64 titanium alloy powder, tungsten carbide powder, tantalum powder and molybdenum powder. It also produces a range of turnkey plasma systems for the production of metal powders. In August, the company revealed plans to invest up to \$128 million over the course of five-years to expand its global manufacturing output and boost R&D capabilities, in a project benefiting from \$33 million in financing from the Canadian government.

[www.tekna.com](http://www.tekna.com) ■

## MPP to relocate and enlarge its MIM operations, diversifies into AM

MPP, a Mill Point Capital portfolio company headquartered in Indiana, USA, will relocate its MIM operations from Westfield, Indiana, to Noblesville, Indiana. Following the move, the facility will be part of the campus on which the company's global headquarters are located. The move is expected to allow for an expansion of current operations, with a significant increase in manufacturing capacity offered by the new 12,800 m<sup>2</sup> (42,000 ft<sup>2</sup>) floor space, double that available at the company's current MIM facility. The company's technical capabilities will be enhanced by the addition of new processing methods, and the site will also be home to MPP Additive Manufacturing.

Dennis McKeen, MPP CEO, commented, "MPP views MIM as an opportunity for fantastic growth. MPP is investing in our Noblesville, Indiana facility to make it the state of the art leader in Metal Injection Molding." MPP supplies MIM components for various markets, primarily for industrial applications. The company's eight production facilities in the US and China specialise in the production of PM and MIM parts for a wide range of industrial applications.

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# Rebound in growth for Japan's Metal Injection Moulding industry

The Japanese MIM industry has reported its first growth in output for seven years, with sales rising to JPY 11.74 billion (\$103.5 million) in 2017 – a healthy increase of 14.5% compared with the previous year (Fig. 1). According to the Japan Powder Metallurgy Association (JPMA), which collects statistical data from the twenty-one companies involved in MIM production in the country, the rise in sales can be attributed to the generally healthy state of the global economy, and several of Japan's MIM producers have indicated plans to expand production capacity to meet increasing demand.

As can be seen in Fig. 1, MIM sales are forecast to rise to JPY 13 billion (\$114 million) in 2019, an increase of 10.7% compared with 2017. The JPMA stated that, by 2020, MIM production in Japan is expected to return to those levels achieved before the financial crisis of 2008. In 2007, MIM production in Japan was reported at its highest level of JPY 15.69 billion (\$138 million).

A breakdown of the application areas for MIM parts produced in Japan (Fig. 2) showed that the industrial machine segment increased its market share to 28.8% in 2017 (previous year 26.7%), while the medical appliances segment rose to 21.3%, compared with 19.9% in the previous year. Automotive applications remained relatively stable at 16.3% (previous year: 16.9%).

The IT segment was down slightly at 8.4% (previous year: 9.1%). MIM component applications in industrial robots are expected to see an increase due to further automation of production lines, and MIM is also expected to see an increase in application in high added value MIM parts for medical appliances. Stainless steels were still by far the dominant materials used to produce MIM parts in Japan, at 69.9% of materials usage (Fig. 3). Magnetic materials followed at 8.7%, with Fe-Ni making up a further 7.9%.

[www.jpma.gr.jp/en/](http://www.jpma.gr.jp/en/) ■

**Sale of MIM parts in Japan**

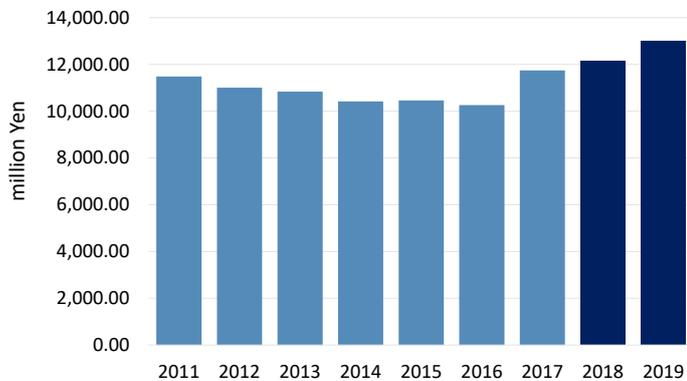


Fig. 1 Sales of MIM products in Japan (FY 2011-2017 with forecasts for 2018 and 2019) (Courtesy JPMA)

**MIM markets in Japan FY2017**

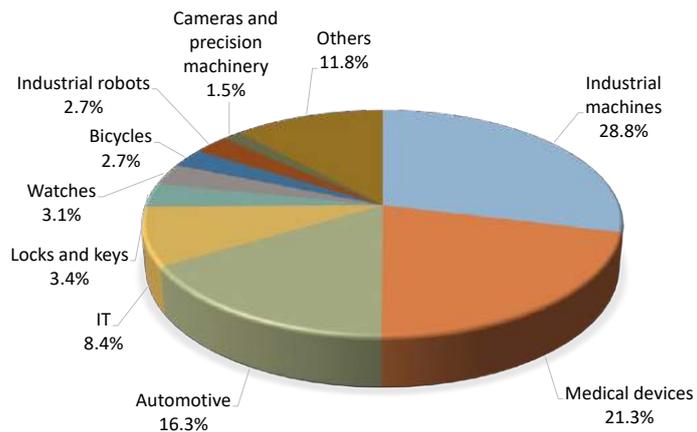


Fig. 2 Breakdown of MIM markets in Japan (FY2017) (Courtesy JPMA)

**MIM materials in Japan FY2017**

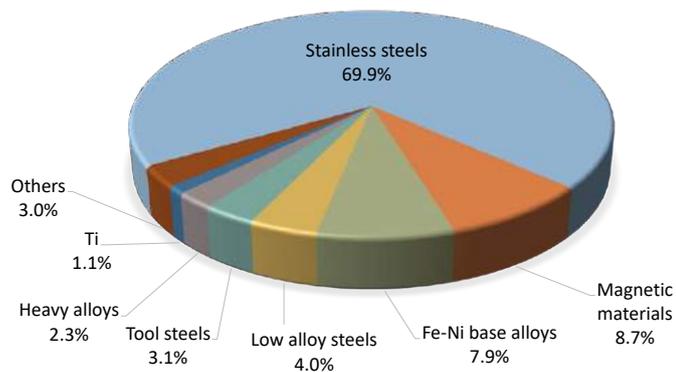


Fig. 3 Distribution of materials used for MIM production in Japan (FY 2017) (Courtesy JPMA)



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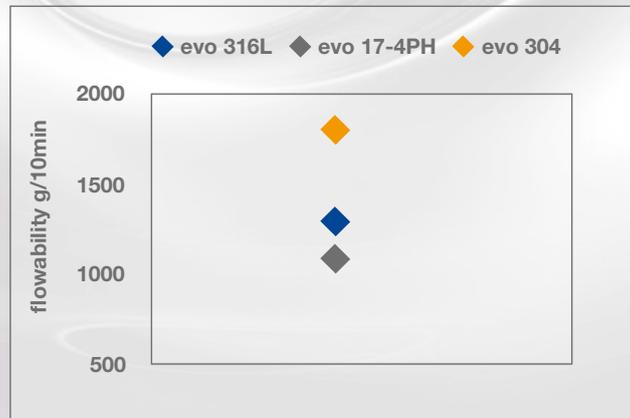
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## LÖMI continues its long-term expansion with investment from GAW Group

LÖMI GmbH, Grossostheim, Germany, has announced an investment by Austria's GAW Group, with the two companies forming a strategic partnership to strengthen the growth of LÖMI's core business of Metal Injection Moulding and Ceramic Injection Moulding debinding systems, as well as broadening its business activities into the solvent-based plastics circular flow economy.

LÖMI is widely considered one of the market leaders for MIM and CIM solvent debinding systems. Its customers include a number of leading MIM and CIM part manufacturers worldwide, for example in the automotive, aerospace, medical and watchmaking industries. Following GAW's investment in the company, management of LÖMI continues to be under its founder José M Dias Fonseca and Christian Ferreira Marques, who continue to hold a substantial share in the company.

A key driver in GAW's decision to invest in the company is said to be its development of a new technology, in cooperation with Fraunhofer Institute for Process Engineering and Packaging (IVV) and a multinational company, capable of selectively solving multi-layer film plastics waste, for example from food packaging, in a non-destructive manner enabling all the contained plastic fractions (PE, PP, etc) to be separated, purified and tailored for subsequent processing in as-new quality.

Ferreira Marques told *PIM International*, "Due to the continuously increasing customer demand, our company's turnover has steadily grown in the last two years by 46 and 65%, respectively, as compared to the year before. Therefore, it was the next logical step for us to find a strategic partner to further our internationalisation and the expansion of our business activities."

"It was important to us in our search that this partner is capable of supporting us in our long-term

goals and that it shares our values such as reliability, innovativeness and cooperative relationships with our customers, staff members and suppliers. We are very pleased to have found the perfect partner with the family-operated GAW Group."

"Research and development has always been a key aspect in manufacturing our systems since the formation of the company in 1991," added Dias Fonseca. "It is our vision to create new and very promising technologies and to achieve their breakthrough. As an example, we introduced our solvent debinding systems to the market in 2001 and, within just a few years, we have become one of the world market leaders. Now we are ready for the next step with our systems for the plastics circular flow economy."

Robert Asst-Pildner-Steinburg and Alexander Rinderhofer, GAW Group, stated, "The prospects for LÖMI are exceedingly positive: the PIM industry keeps on growing rapidly, in addition more and more PIM part producers are switching to the solvent debinding process. Furthermore, the demand for clean processes will increase over the course of the next few years due to tightened legislation regarding environmental protection

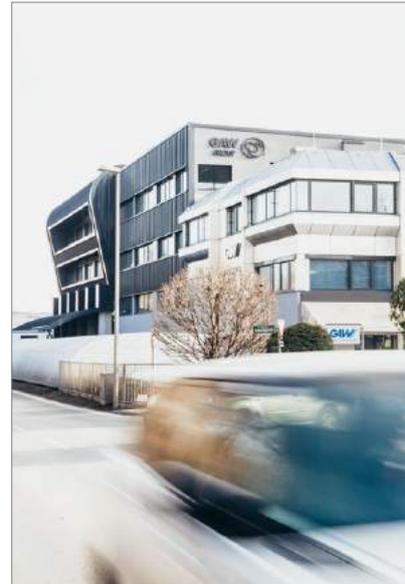


Fig. 1 The corporate headquarters of GAW Group in Graz, Austria

and occupational health and safety. The high-quality recovery of plastic material is a social responsibility that GAW Group and LÖMI are glad to meet together now."

With solvent debinding, many different kinds of feedstock can be processed by a large number of solvents. This enables part producers to test new feedstock or binder systems and to optimise their processes without becoming dependent on a single feedstock producer.



Fig. 2 LÖMI's Managing Partners Christian Ferreira Marques (left) and José M Dias Fonseca (right) (Courtesy LÖMI)



Fig. 3 LÖMI's MIM/CIM solvent debinding system EBA-300 with a solvent recovery system MDA-100. The control cabinet contains a touch panel with real-time process parameter display (Courtesy LÖMI)



Fig. 4 Three LÖMI EBA-900 MIM/CIM debinding systems with a parallelly operated MDA-3000 solvent recovery system shortly before initial operation at a large Indian PIM part producer (Courtesy LÖMI)

"Furthermore, our solvent debinding systems are very compact in their dimensions and, through their little wear and tear and low energy consumption, they are very economic in their operation," commented Dias Fonseca. "The solvent is continuously reprocessed with a rate of up to 99% by a solvent recovery system and returned to the process in a closed system. This makes our systems very safe and environmentally beneficial."

"Currently, many MIM and CIM part manufacturers are switching to the solvent debinding process," continued Ferreira Marques. "For example, one single customer in the watchmaking industry operates fifteen of our systems, and the world's largest PIM part producer uses thirty-six large-scale LÖMI plants so far."

The company's debinding systems are available with 15–1,200 litres of batch loading volume and can be extended on a modular basis. The PLC-operated front loaders perform the drying of the parts directly after the debinding process, therefore saving one handling step of the parts, while a touch display shows real-time process parameters and facilitates process control. A large number of standardised part trays and mobile loading carts save time and costs while charging the systems.

LÖMI added that it continuously enhances its debinding systems in close cooperation with feedstock and part producers. For example, its debinding systems for CIM have been optimised with regard to the requirements of part manufacturers in the medical and watchmaking industries: in order to avoid an accumulation of superfine particles on the parts' surfaces, the debinding process has been modified and the loading mechanism for the part trays in the process chamber replaced by an abrasion-free alternative. Also, to ensure that the oftentimes very small and lightweight parts stay in their places on the part trays during the process, a custom-designed filling process was installed.

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## China's specialist MIM powder producers expand production to meet growth

The 2018 World Congress on Powder Metallurgy (WORLDPM2018), held in Beijing, China, September 16-20, 2018, highlighted the high rate of growth that has been achieved globally in Metal Injection Moulding part production over the past decade, and more specifically the contributions made by China's MIM producers and powder suppliers to this growth. This contribution was very evident in the number of specialist Chinese powder producers, some of which are relatively new to the field, which exhibited at World PM2018.

Speaking to Bernard Williams on behalf of *PIM International*, most of those specialist powder companies who exhibited at the World Congress stated that they were in the process of increasing production capacity

for fine spherical powders in order to meet the continuing growth in demand from both the MIM and metal AM sectors. A number of companies reported that they are using advanced processes such as combined high-pressure water and gas atomisation to produce the MIM-grade powders.

### Tianjin Zhujin Technology Development Ltd

Established in 1990 in Beichin, Tianjin, this company produces a range of Fe-, Ni- and Co-based alloy powders for thermal spraying, hardfacing and other applications.

Since its founding, the company has further refined its gas atomisation technology to develop alloy powders for Powder Metallurgy, Metal Injection Moulding and

metal Additive Manufacturing for high-performance applications, including a complete range of stainless steel powders having fine particle size, low O<sub>2</sub> content and high sphericity. The most recent expansion in powder production facilities is reported to have taken the company's annual capacity to around 30,000 tonnes.

### Advanced Technology (Bazhou) Special Powder Ltd

A joint venture between AT&M and Hebei Hengxin Trading Ltd, the company was established in Bazhou City, Hebei Province, in October 2017. Powder production lines using gas and water atomisation were transferred from AT&M in Beijing to Bazhou and, with additional new atomisation lines, the company will have annual capacity of 10,000 tonnes – making it one of the largest specialist powder manufacturers in China. Powders are produced for MIM, soft magnets, diamond tools, automotive parts and filters.



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**Yingtan Longding New Materials & Technologies Ltd**

Established in the Haidian District of Beijing in 2011, this company produces atomised powders for MIM using advanced gas and water atomisation, as well as a combined gas and water atomising process. The company reported sales of 2,700 tonnes in 2017 and is expanding production with a new powder plant that will go on stream in 2019, having a capacity of 5,000 tonnes/year.

**Changsha Hualiu Metal Powders Ltd**

Changsha Hualiu Metal Powders, or HL Powder, is based in Changsa, Hunan Province, and currently operates six gas atomisers having annual capacity of around 3,600 tonnes for stainless steel, soft magnetic and other special alloy powders. The powders are produced primarily for use in MIM, metal Additive Manufacturing, powder cores, etc.



China's MIM powder producers featured prominently at WORLDPM2018



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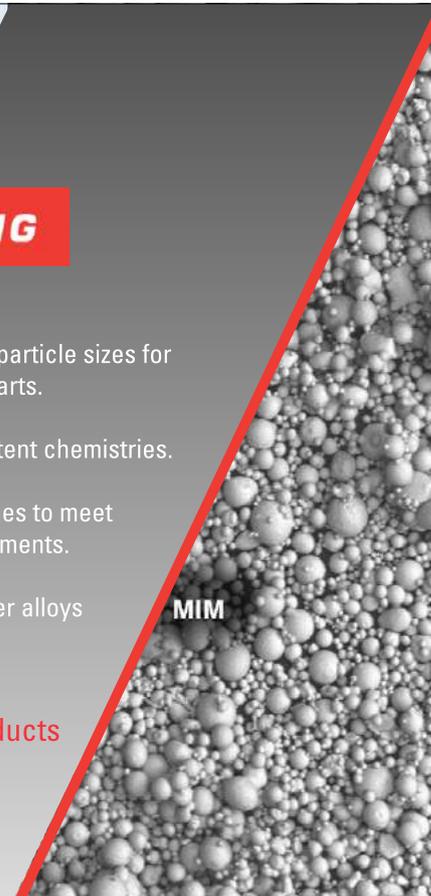
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**Jiangxi Yuean Superfine Metal Ltd**

Formerly known as Yuelong Powders, the company is located in Jiangxi Province and is one of Asia's leading producers of carbonyl iron powders (CIP). The company has also established a leading position in China as a supplier of MIM feedstock using its CIP powders and, in 2010, added water and gas atomisers for the production of high-quality stainless steels, iron-based alloys, Ti and Ti alloy powders for use in MIM as well as Additive Manufacturing.

**Huijing Atomizing Science Ltd**

Based in Deqing, Huzhou Province, the company has been manufacturing a range of metal and alloy powders for MIM since 2000. The company introduced high-pressure water atomisation technology to produce fine, spherical stainless steel powders in 2006 (having D50 particle size of 7.5 µm). The 316L stainless powder is said to have an oxygen content of around 2500 ppm and can be sintered to 7.85 g/cm<sup>3</sup> density. In 2015, it began production of Ti alloy powders.

**Lide Powder Material Ltd**

Lide Powder Material is based in Shijiazhuang, Hebei Province, and has been producing MIM-grade powders (mainly stainless steels) for around ten years. It now has six production lines using its super-high pressure water-gas atomisation technology, giving an annual capacity of 4,600 tonnes of metal and alloy powders. The company states that its F75 grade Co-Cr atomised powder is used to produce the MIM camera frame used in the casing of Apple's iPhone X.

**VTECH**

VTECH, part of Vday Additive Manufacturing Technology Ltd, based in Changsha, Hunan Province, produces a range of micro and nano powders from Ti alloys, Ni-based superalloys, stainless steel and high alloy steels, suitable for both MIM and metal AM. It also produces a range of amorphous alloy powders.

**CNPC Powders**

CNPC Powders recently completed the construction of a new 30,000 m<sup>2</sup> facility in Fengyang, Anhui, that will have an annual production capacity of 3,500 tonnes of metal powders for AM, MIM and other applications. The powders produced will include iron and copper alloys, Ni-base alloy, Ti alloys, stainless steels, Co-based alloys and electrolytic copper and chromium powders.

**DAYE Metal Powder Ltd**

DY Powder has been based in Yuanshi County, Shijiazhuang Province, since 1998, producing MIM and AM-grade stainless steel powders by a combination of ultra-high pressure water and gas atomisation. The fine, nearly spherical atomised particles have a smooth surface and an O<sub>2</sub> content of 2200 ppm at D50 of 12 µm. ■

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## Cremer Thermoprozessanlagen receives Fachmetall's PM Qualification Award

Cremer Thermoprozessanlagen GmbH, Düren, Germany, has received the Fachmetall PM Qualification Award 2018 from Fachmetall GmbH, Radevormwald, Germany, a metallurgical laboratory specialising in investigations of Powder Metallurgy and wrought materials. The award is said to recognise Cremer for 'outstanding services to the global Powder Metallurgy industry,' and was accompanied by a certificate and a commemorative sculpture.

Cremer is a manufacturer of steam treatment and sintering furnaces for Powder Metallurgy applications. The company's MIM-Master, a continuous sintering furnace for Metal Injection Moulding based on the walking-beam technique, has played a key role in the success of MIM technology over the past twenty-five years.

Holger Davin, Managing Director of Fachmetall, presented the award to Ingo Cremer, Managing Director of Cremer Thermoprozessanlagen, during the company's annual awards

presentation. With the Fachmetall PM Qualification Award and QM Context Award, Fachmetall stated that it aims to draw the attention of the public to companies with excellent Powder Metallurgy and Quality Management activities.

[www.cremer-polyfour.de](http://www.cremer-polyfour.de)  
[www.fachmetall.de](http://www.fachmetall.de) ■



*Ingo Cremer (centre) accepts Fachmetall's PM Qualification Award from Holger Davin (left) and Georg Schlieper (right) (Courtesy Fachmetall GmbH)*



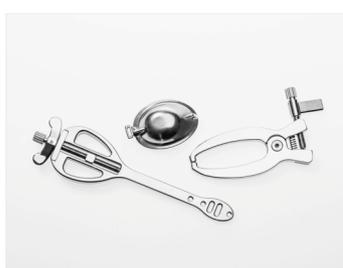
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## Strong demand drives titanium powder capacity expansion at Osaka Titanium Technologies

Osaka Titanium Technologies Co., Ltd., Amagasaki, Hyōgo Prefecture, Japan, is expanding its powder production capacity to meet increasing demand for titanium alloy powders. The company will invest approximately JPY 1 billion (approx. \$8.8 million) in a new factory with a planned powder production capacity of 100 t/year, expected to open in early 2020.

The company has been manufacturing titanium low-oxygen powders using gas atomisation since 1994, primarily for use in sputtering targets, in liquid crystal displays and in Metal Injection Moulding. As the adoption of metal Additive Manufacturing grows, however, it has seen both domestic and international customers express their need for a safe and reliable system for the delivery of high-quality

alloy powders for use in the industry.

The company stated that it has seen the highest demand for titanium alloy powders from the aerospace and medical industries. As such, it will aim to secure aerospace quality certification to AS9100 for the new factory as soon as is possible.

Along with the new factory, Osaka Titanium Technologies has established a new team, the AMPM Team, to combine sales and technology for accelerated market development and expansion of the company's alloy powder activities. One key area in the company's development of higher performance titanium powder is the use of its in-house manufactured titanium sponge material as feed-stock, which could offer heightened control over powder quality.

[www.osaka-ti.co.jp](http://www.osaka-ti.co.jp) ■

## EPMA PM Thesis Competition 2019 now open for submissions

The European Powder Metallurgy Association has launched its 2019 Powder Metallurgy Thesis Competition, sponsored by Höganäs AB, and is accepting entries via its website. The deadline for submissions is April 24, 2019.

This competition is open to all graduates of a European University whose theses have been officially accepted or approved by the applicant's teaching establishment during the previous three years. Theses, which must be classified under the topic of Powder Metallurgy, including Metal Injection Moulding, are judged by an international panel of PM experts drawn from both academia and industry.

[thesiscompetition.epma.com](http://thesiscompetition.epma.com) ■

## Melrose issues latest trading update for GKN

Melrose Industries plc has issued a trading update for the four months from July 1–October 31, 2018. The group acquired GKN plc in April 2018 after receiving the support of GKN's shareholders. According to the update, Melrose has seen strong revenue growth in the Aerospace and Powder Metallurgy segments, with the group currently trading in line with the board's expectations for 2018.

The Powder Metallurgy division achieved revenue growth in the period of 9% compared to the same period in 2017, with improved margins. The group stated that this positive result offers confidence that the 14% margin target for the division will be achieved in the medium term.

The Aerospace division achieved revenues up 6% compared to the same period in 2017, and good

progress is said to have been made on margin, including improvements to the division's performance in North America. Melrose stated that, with an experienced and incentivised management team, the division is making the necessary improvements to achieve acquisition objectives.

Revenue in the Automotive division was flat for the period compared to 2017. The margin was reported to be lower, but Melrose stated it expects planned operational improvements identified at the time of its acquisition to positively impact performance in 2019. In November 2018, Liam Butterworth was appointed as the new CEO of the Automotive division and a new management team is currently being assembled from various internal and external sources with the aim of further enhancing the performance of the business.

Overall, Melrose stated that it is confident the GKN businesses it acquired in April 2018 will offer good opportunities for value creation over the medium term. The group will present its full year results in March 2019 and will host a Capital Markets Day in London, UK, on April 3, 2019, focused on its Aerospace and Automotive divisions.

Christopher Miller, Melrose Chairman, stated, "Melrose has a proven business model, which has been successful over many years and through several economic cycles. We are confident that there is an outstanding opportunity to make significant and lasting improvements to the performance of the GKN businesses. Whilst certain end markets may be unpredictable, the group is on track to meet our expectations for this year. We are excited by the future prospects of the group and look forward to delivering significant value for shareholders."

[www.melroseplc.net](http://www.melroseplc.net) ■

## Fraunhofer IKTS introduces Fused Filament Fabrication for hardmetals

Researchers at the Fraunhofer Institute for Ceramic Technologies and Systems (IKTS) in Dresden, Germany, report that they have adapted the Fused Filament Fabrication (FFF) process for the Additive Manufacturing of hardmetals. Extremely hard tools produced from hardmetals consisting of the metal binders nickel or cobalt and the hard phase tungsten carbide, are required in forming technology, metal-cutting and process engineering.

Cutting, drilling, pressing and punching tools made from hardmetals have conventionally been extruded, Metal Injection Moulded or produced using uniaxial or Cold Isostatic Pressing. However, although these methods can achieve a high degree of hardness,

they often require complex and expensive post-processing steps to achieve net shape.

Additive Manufacturing enables the production of components with complex geometries with minimal post-processing, but has traditionally been limited in terms of the hardness and component size which can be achieved. Both metal Binder Jetting and thermoplastic-based AM have been successfully used at IKTS with selected hardmetal compositions; however, the metal binder content and resulting hardness, as well as the size of these components, has been limited.

According to the IKTS, Fused Filament Fabrication could enable economical and customisable production of even harder tools for

the first time. Originating in the plastics processing industry, FFF was initially adapted for ceramics and composite materials at IKTS.

During this process, parts are manufactured from a flexible, melt-able metal filament. Depending on the material's structure, a reduced grain size and binder content can be used to specifically increase the hardness, compressive and flexural strength of hardmetal filaments.

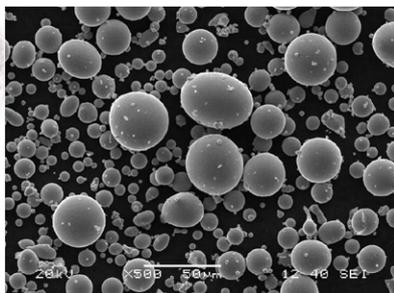
Dr Johannes Pötschke, who heads the Hardmetals and Cermets group at IKTS, explained, "The filaments can be used as semi-finished products in standard printers and, for the first time, make it possible to print hardmetals with a very low metal binder content of only 8% and a fine grain size below 0.8 µm and thus allow extremely hard components with up to 1700 HV10."

[www.ikts.fraunhofer.de](http://www.ikts.fraunhofer.de) ■



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## ARC Group Worldwide announces first quarter 2019 results

ARC Group Worldwide, Inc., DeLand, Florida, has reported the results for its first fiscal quarter 2019, ending September 30, 2018. Fiscal first quarter 2019 revenue was reported at \$20.6 million, compared to \$19.1 million for the fiscal first quarter 2018. This increase in revenue was primarily driven by higher MIM and plastics component sales, due to the combination of higher sales with higher order volumes in the aerospace, medical and firearms and defence markets.

Fiscal first quarter 2019 gross profit was reported to be \$3.1 million, compared to a gross profit of \$1.2 million in the company's fiscal first quarter 2018. This increase was said to be primarily the result of cost reduction initiatives completed during the fiscal year 2018 and the company's continued diversification into higher margin aerospace and medical parts.

The effectiveness of cost reduction initiatives was said to be visible in both the Precision Components Group and Stamping Group, as sales increased by approximately \$1.5 million in fiscal first quarter 2019 over fiscal first quarter 2018; however, gross profit increased by approximately \$1.9 million over the same periods. Contributing to the increase in gross profit was an adjustment decreasing cost of sale by \$1.0 million for an out-of-period adjustment identified during fiscal first quarter 2019 and recorded in the same period.

ARC Group stated that its planned sale of the 3D Material Technologies (3DMT) division has been progressing as expected. Management presentations have begun to be made to interested parties and, based on current projections, the company expects to sell 3DMT before the end

of the third-quarter fiscal year 2019, with the funds being used to pay down debt.

Alan Quasha, ARC's CEO, commented, "I am pleased that the company continues on its path to increased profitability, particularly as compared to the prior year. We expect this trend to continue. Our first quarter of fiscal year 2019 has vastly improved over our first quarter of fiscal 2018, with sales up \$1.5 million and gross profit and EBITDA up approximately \$2 million. We have been able to grow in an efficient and targeted manner while improving our bottom line."

"The previous shift in internal goals will continue to focus our core divisions on making sound business decisions that lead to profitable growth for our future. The quarterly results demonstrate progress towards these goals and illustrate how we are driving the company forward," he continued.

[www.arcgroupworldwide.com](http://www.arcgroupworldwide.com) ■

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## PyroGenesis completes construction of new metal powder production facility

PyroGenesis Canada Inc., Montreal, Canada, has completed the construction of its new facility for the production of metal powders for Additive Manufacturing and MIM. The facility houses a new plasma-based atomisation unit, inventory storage and logistics operations and will be dedicated to the production of plasma atomised Ti-6Al-4V powders, primarily targeting the aerospace and biomedical industries.

Massimo Dattilo, Vice President of PyroGenesis Additive, stated, "We are very excited about having completed this milestone. It puts PyroGenesis squarely on the map as a quality supplier of Ti-6Al-4V powder for the



*PyroGenesis has completed construction of its new facility for metal powder production for AM (Courtesy PyroGenesis Canada Inc.)*

AM industry. In parallel, we are also investigating other materials which can be produced with our other reactors, currently in our main facility."

"This next logical step of incorporating some of the previously announced improvements into a cutting-edge facility is now complete," added P Peter Pascali, President and CEO of PyroGenesis. "After investing over \$2.5 million into this facility,

all that remains is to incorporate post-treatment equipment for it to be a standalone facility."

The new facility is ISO 9001:2015 certified and is expected to be AS9100D (aviation, space and defence) certified by the end of 2018. Upon receipt, PyroGenesis will then pursue ISO 13485 for the production of medical devices.

[www.pyrogenesis.com](http://www.pyrogenesis.com) ■



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## GeniCore showcases U-FAST sintering system at Euro PM2018

GeniCore, Warsaw, Poland, showcased its new U-FAST sintering system at the recent Euro PM2018 Congress & Exhibition in Bilbao, Spain. The system uses a Spark Plasma Sintering (SPS) technology, producing electric pulses of under 1 ms. In GeniCore's U-FAST (Upgraded Field Assisted Sintering Technology) method, the energy source is an impulse power supply with an operating voltage similar to that used in FAST or SPS type sintering. It can be used to sinter metal materials up to a maximum temperature of 2500°C, with a maximum pressing force of 350 kN.

U-FAST sintering can reportedly be used to produce high-performance ceramics, metal matrix composites, superhard materials, functionally gradient materials and MMC composites with uniform microstructure and good physical properties.

Other products offered by GeniCore include innovative materials such as Diamond Enhanced Cemented Carbide (DEC), produced using its Pulse Plasma Compaction (PPC) sintering method. DEC is described as a superhard



GeniCore's U-FAST sintering system uses SPS technology, producing electric pulses of under 1 ms (Courtesy GeniCore)

material with a very high hardness to impact resistance ratio.

GeniCore solutions are used by customers in the tooling, power, electronics, automotive and firearms industries. The company stated that it is focused on establishing long-term cooperation with clients globally, including further development of its sales and service network.

[www.genicore.pl](http://www.genicore.pl) ■



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## EPMA's Metal Injection Moulding Seminar scheduled for June 2019

The European Powder Metallurgy Association (EPMA) will hold a Metal Injection Moulding Seminar at the headquarters of Swiss MIM specialist Parmaco AG in Fischingen, Switzerland, June 4-5, 2019. The last EPMA MIM seminar was held at BASF SE in Ludwigshafen, Germany, in June 2017.

Titled 'A Two-Day Seminar for the Entire MIM Supply Chain', the event will host speakers from the MIM industry for an exploration of the future of MIM, design criteria and secondary operations, quality concepts and materials. Also featured will be case studies of MIM components and their advantages over components made by alternative manufacturing processes.

A showcase of MIM parts will be available during the event to view and to help further discussions during networking sessions. Companies can register their interest in contributing parts to the MIM showcase by contacting the EPMA. The 2019 MIM Seminar is organised by the EPMA's EuroMIM group with support from the sectoral group members.

[www.epma.com/seminars](http://www.epma.com/seminars) ■

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# Ceramic Additive Manufacturing market to exceed \$3.6 billion by 2028, finds report

Additive Manufacturing industry analysis and consulting firm SmarTech Publishing, Crozet, Virginia, USA, has released the new edition of its study on the emerging ceramic Additive Manufacturing market. The report, 'Ceramics Additive Manufacturing Markets 2017-2028', projects that the market will generate overall revenues of over \$3.6 billion, driven by strong compound annual growth rates (CAGR) in end-use part production by 2028.

This is the second report published by SmarTech on the ceramic AM market and includes up-to-date market data and analysis of market trends at the professional and industrial level. The report breaks down opportunities for ceramic AM across numerous user industries, as well as different AM technologies, materials and material supports, part types and geographical market regions.

The report also analyses some of the pros, cons and revenues generated by the dominant AM technologies for processing ceramics. These include material extrusion, photopolymerisation and Binder Jetting technologies. Currently available high-end industrial system data are complemented by an in-depth analysis of new and emerging technologies, such as low-cost hardware systems and new jetting processes, and all analysis is supported with hardware and material market shipments, sales, installations and future forecasts through 2028.

In 2018, SmarTech states, the ceramic AM market is focusing on part production, benefiting from the experience acquired by adopters and system OEMs working with metal and polymer technologies. Ceramic AM, however, presents a distinct set of advantages and challenges, which SmarTech addresses along with the latest successful use cases. Companies developing materials and providing ceramic AM services or specific applications, the firm

stated, have come to understand that the excellent geometric capabilities offered by AM can be ideal for the production of complex ceramic parts in all major ceramic adoption segments.

Segments in which ceramic AM is seeing rapid rates of adoption are said to include the aerospace, automotive, marine, energy, electronics, medical, dental and biomedical segments, which have also been among the first wave of adopters of metal and polymer AM technologies. Major companies in the ceramic AM market which are addressed within the report include Lithoz, 3D Ceram Sinto, Admatec, Prodways, Tethon 3D, 3D Systems, Kwambio, Voxeljet, ExOne, HP, Johnson Matthey, Nanoe, XJet and more.

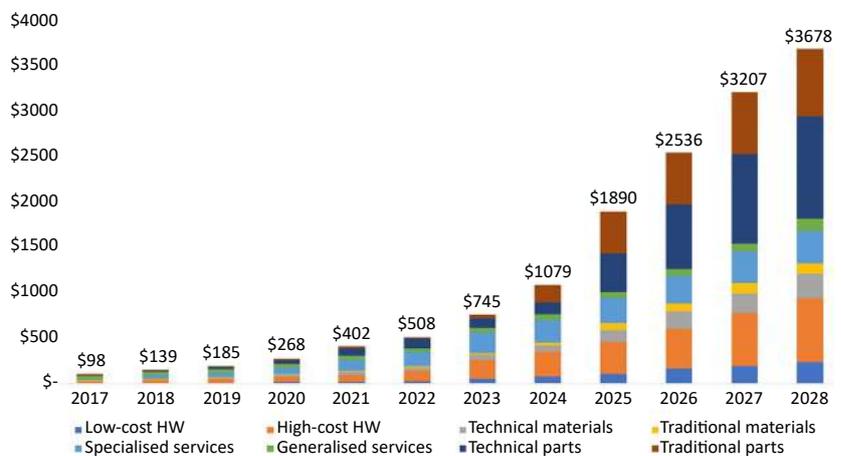
### Highlights from the report:

- According to SmarTech's forecast timeline, ceramic AM adoption will experience an inflection point after 2025 as the major AM technologies that support ceramics production reach maturity and enjoy a sufficient presence in the market to support serial production. The adoption of CIM-based

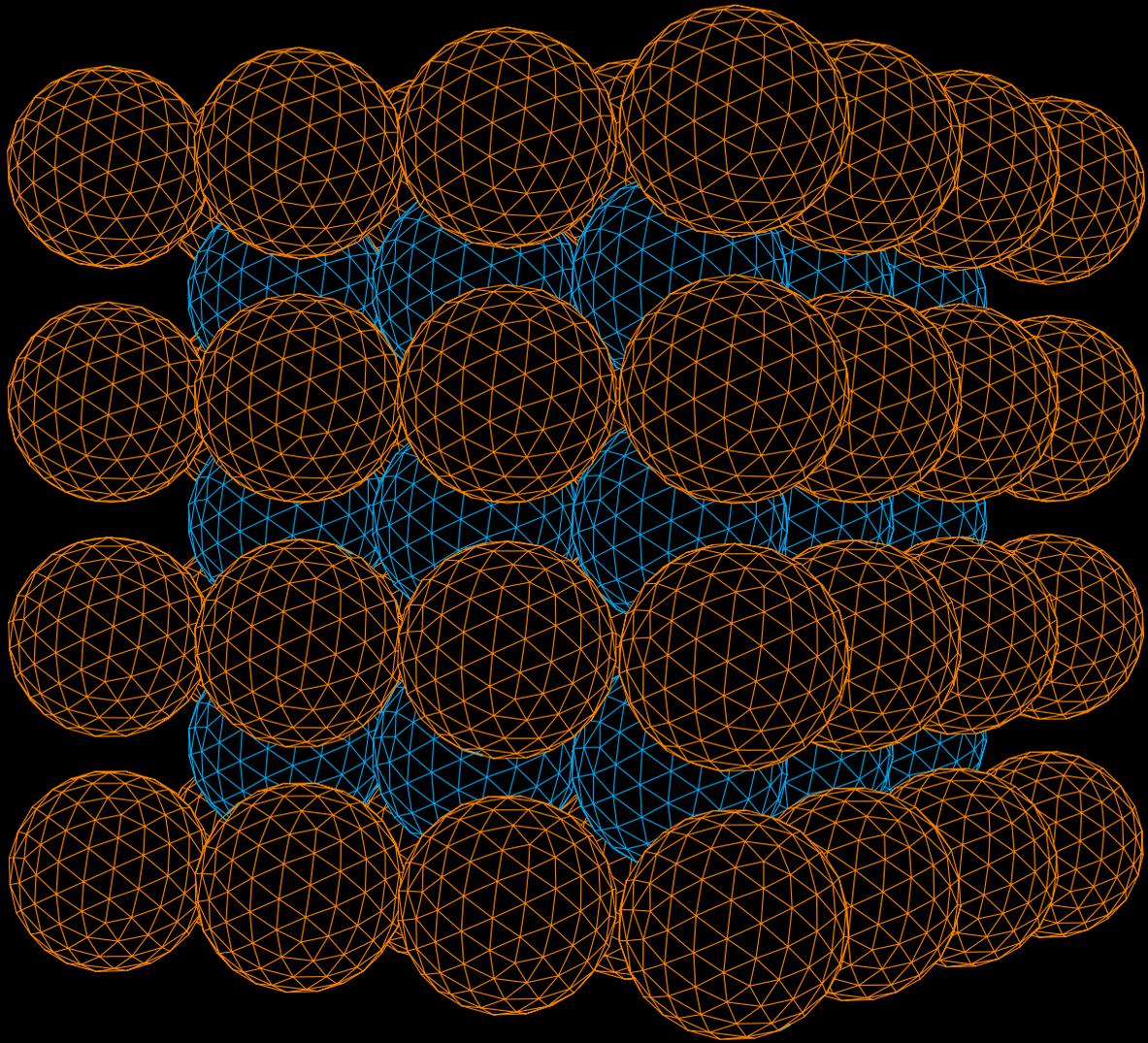
AM processes is expected to drive larger batch production in the same way as the adoption of Metal Injection Moulding-based processes is currently expanding metal AM adoption, by increasing throughput capabilities and lowering costs.

- The final parts value for both technical and traditional ceramic parts is expected to represent the most significant opportunities driving the market for the medium- to long-term future. Compared to the relatively low revenues generated by technical and traditional ceramic materials, SmarTech stated that this trend indicates that, in ceramic AM, more than in any other material family, the primary value is in the process. This means that additively manufacturing a ceramic part increases the value of the material used to produce it several times.
- Ceramic AM technologies are now largely available, so the biggest challenge to address today is the creation of market demand. Companies that produce ceramic components, especially advanced ceramic components, could benefit significantly from subassemblies and ceramic parts designed for AM.

www.smartechpublishing.com ■



SmarTech's report forecasts that the ceramic AM market will grow significantly from 2017-2028, driven by strong compound annual growth rates in end-use part production (Courtesy SmarTech Publishing)



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## Carpenter announces acquisition of LPW Technology

Carpenter Technology Corporation, Philadelphia, Pennsylvania, USA, has acquired LPW Technology Ltd for approximately \$81 million. LPW develops and supplies advanced metal powders and lifecycle management solutions to the metal Additive Manufacturing industry. It is based in Widnes, Cheshire, UK, and has additional processing operations near Pittsburgh, Pennsylvania, USA.

Tony R Thene, Carpenter's President and Chief Executive Officer, stated, "Our aggressive development in key aspects of Additive Manufacturing demonstrates our commitment to build on our industry-leading position in this space. The acquisition combines LPW's metal powder lifecycle management technology and processes with our technical expertise in producing highly engineered metal powders

and additively manufactured components." Carpenter stated that lifecycle management technology is becoming increasingly important to understanding how materials behave before, during and after production in Powder Bed Fusion Additive Manufacturing. Understanding powder behaviour will continue to be critical as AM becomes more widely adopted and implemented across various industries.

"LPW's innovative platforms and enabling technology further solidify Carpenter's position as a preferred provider of end-to-end next-generation Additive Manufacturing solutions," commented Phil Carroll, LPW's founder. "I'm extremely proud of the accomplishments we've achieved at LPW and I'm excited to be part of Carpenter's continued growth and leadership in AM."



LPW Technology's headquarters in Widnes, Cheshire, UK (Courtesy LPW Technology)

Carpenter's AM portfolio also includes recent investments in Puris, a titanium powder producer; CalRAM, a leader in Electron Beam and Laser Beam Powder Bed Fusion AM services; and the construction of an Emerging Technology Center in Athens, Alabama, USA. The company stated that these recent acquisitions and investments represent a significant force positioned to capitalise on the rapid growth of the AM industry.

[www.cartech.com](http://www.cartech.com)

[www.lpwtechnology.com](http://www.lpwtechnology.com) ■

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## International Conference on Injection Molding of Metals, Ceramics and Carbides

Registration has opened for MIM2019: the International Conference on Injection Molding of Metals, Ceramics and Carbides, to be held in Orlando, Florida, USA, February 25–27, 2019. MIM2019 is a global conference and tabletop exhibition that highlights advances in the Powder Injection Moulding industry.

The annual conference is sponsored by the Metal Injection Molding Association, a trade association of the Metal Powder Industries Federation (MPIF) and its affiliate APMI International. Highlights of MIM2019 are set to include:

- A keynote address by Robert Dowding, U.S. Army Research Laboratory
- Tabletop Exhibition & Networking Reception (refreshments sponsored by *PIM International*)
- The annual PIM Tutorial presented by industry veteran Randall M German, FAPMI, Prof Emeritus, San Diego State University

“The annual MIM conference is an excellent place for product designers, engineers, consumers, students and more, to network and broaden their industry knowledge,” explained Jim Adams, Executive Director/CEO, Metal Powder Industries Federation. Last year’s MIM2018 welcomed more than 180 attendees representing 104 companies from sixteen countries.

Attendees in 2018 consisted of 35% parts manufacturers; 23% equipment and service providers; 17% powder and feedstock suppliers; 14% consumers; and 11% other. A similar attendance base is expected for 2019.

[www.mim2019.org](http://www.mim2019.org) ■

## Euro PM2019 Congress & Exhibition heads for the Netherlands

Euro PM2019, the EPMA’s annual Powder Metallurgy congress and exhibition, will be held in Maastricht, the Netherlands, October 13-16, 2019, at the Maastricht Exhibition & Congress Centre (MECC). According to the EPMA, Euro PM2019 is set to feature a world-class technical programme as well as a 5000 m<sup>2</sup> exhibition, showcasing the latest

developments from the global PM supply chain.

The conference programme of plenary, keynote, oral and poster presentations will focus on all aspects of Powder Metallurgy, including Structural PM Parts, Additive Manufacturing, MIM, HIP and Hard Materials.

[www.europm2019.com](http://www.europm2019.com) ■

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## Chinese MIM networking forum to target end-users

A high-level Metal Injection Moulding networking forum and exhibition will take place in Dongguan City, Guangdong Province, China, from December 20-21, 2018. The event is attracting leading MIM producers and their customers from throughout China, alongside local government officials and delegates from related industries.

Since 2013, the Metal Injection Moulding industry has expanded significantly in China, largely due to the surge in demand for consumer electronics or 3C products such as smartphones and laptops, notably Apple's iPhone and Macbook ranges. Relevant manufacturers from these and other key MIM markets have been invited to give a talk on the outlook for 2019 during the conference.

During the forum Dr Qiu (Yang Hung, Chiou) will hold a panel discussion with a number of MIM experts on the future of the technology and the market, based on nearly ten years of practical experience promoting MIM and Ceramic Injection Moulding technology in China. In order to promote communication and learning

throughout the MIM community, the conference organisers have made participation in the forum free to MIM manufacturing company employees and customers.

In addition, the PM China exhibition has published a list of more than three-hundred MIM-related enterprises including factories, materials producers (powder, feedstock and binders), and equipment manufacturers, available to access on the event website. The organisers stated that they hope the publication of this list, potentially representing more than half of the world's MIM manufacturers, will enhance opportunities for collaboration between companies while also serving to highlight China's contribution to the global MIM industry.

The event is organised by New Alliance (Shanghai) Exhibition Services Co., Ltd., the China Steel Structure Association Powder Metallurgy Branch and the Guangdong Powder Metallurgy Industry Technology Innovation Alliance. For more information contact [echo.lu@unifair.com](mailto:echo.lu@unifair.com) ■

## New MPIF Standard 35 for Metal Injection Moulding

The Metal Powder Industries Federation (MPIF) has released its new Standard 35-MIM – Materials Standards for Metal Injection Molded Parts. The standard aims to provide design and materials engineers with the latest engineering property data and information available in order to specify materials for components made using Metal Injection Moulding.

The standard was developed by the MIM commercial parts manufacturing industry and includes new data for low-alloy steels, MIM-4605 (HIPed quenched and tempered) and stainless steels, MIM 17-4 PH (H975) and MIM-17-4 PH (H1025).

Standard 35-MIM does not apply to materials for Powder Metallurgy structural parts, PM self-lubricating bearings, or powder forged products; these are covered in separate editions of MPIF Standard 35.

The new standard is available to purchase via the MPIF's publication portal.

[www.mpif.org](http://www.mpif.org) ■

## Triditive launches metal AM platform based on BASF's Ultrafuse feedstock

Triditive, an Additive Manufacturing machine maker based in Gijón, Spain, has launched the AMCell, a hybrid and automated Additive Manufacturing machine said to be capable of producing up to 10,000 green parts per month using BASF's Ultrafuse 316LX filament.

Enabled by its control software and remote monitoring, the integrated system is aiming to make Additive Manufacturing a viable solution for high-volume manufacturing, 24/7.

According to Triditive CEO Mariel Diaz, "The green parts printed with

AMCell using BASF's metal filament solution meet the geometric and surface quality requirements for mass-manufacturing of final parts. The controlled build chamber environment in the AMCell and its optimised extrusion process achieve part porosities similar to those that are typically obtained from Metal Injection Moulding technology."

BASF's Ultrafuse 316LX filament is a metal-polymer composite comprising austenitic stainless-steel type 316L powder. Tailored to existing, high-throughput

MIM industry standard catalytic debinding and sintering, final metal parts can be produced in high quality.

AMCell's automated manufacturing of large batches and the use of Ultrafuse 316LX are said to greatly ease material handling processes by eliminating potential hazards inherent in other metal powder AM processes. The automatic load and consumption control of Ultrafuse 316LX filament spools allows the system to operate largely unsupervised during the whole production process and reduces labour and human intervention to a minimum.

[www.triditive.com](http://www.triditive.com) ■

## Desktop Metal targets MIM with upgraded Production System for high-volume AM

Desktop Metal, based in Burlington, Massachusetts, USA, has announced a number of major advancements and expanded capabilities to its Production System, a metal Additive Manufacturing machine developed for mass production of complex metal parts. At Formnext 2018, November 13-16, Frankfurt, Germany, the company showcased the updated system and displayed a wide range of metal additively manufactured parts produced on the new machine.

The installation of the first Production System is scheduled for Q1 2019 at a Fortune 500 company among Desktop Metal's early Pioneer customers. Additional customer installations at major automotive, heavy duty and leading metal parts manufacturers will follow throughout 2019, with broad availability expected in 2020.

"We are excited to provide the international engineering and design community with deeper insights into the power of the Production System with updated innovations and an extensive display of metal parts to be publicly shown for the first time this week," stated Ric Fulop, CEO and Co-founder of Desktop Metal. "As we continue to expand our list of global customers and partners, companies that are turning to the game-changing technology available with the Production System, and installations set to begin rolling out in the coming months, Desktop Metal is looking to further shift the industry beyond prototyping to now include full scale metal manufacturing."

Powered by Single Pass Jetting technology, the Production System is said by Desktop Metal to be more than four times faster than any Binder Jet competitor and offers a hundred times speed improvement over any laser-based system. Since it was first introduced, advancements to the technology and capacity of the

Production System have expanded to include:

- Accelerated printing speeds to 12,000 cm<sup>3</sup> per hour
- Expanded build volume of 750 x 330 x 250 mm, a 225% improvement, designed for higher throughput and efficiency
- Two full-width print bars, advanced powder spreaders and anti-ballistic system that work to spread powder and print in a single quick pass across the build area
- Use of 32,768 piezo inkjet nozzles that enables binder chemistries to print an array of metals – including tool steels, low-alloy steels, titanium and aluminium – at a rate of 3 billion drops per second

- Offers a Binder Jet system with an industrial inert environment, including gas recycling and solvent recovery, to safely print reactive metals in mass production
- Capability to print more than 60 kg of metal parts per hour.

### Examples of components produced on the Production System

In addition to the Production System, Desktop Metal also showcased additively manufactured metal parts for applications across industries, demonstrating the range and complexity now achievable using the system.

### Spauger bit

The spauger bit, by Milwaukee Tool®, features complex geometry traditionally requiring multiple manufacturing steps to produce, including time-consuming, dedicated set-ups for milling, turning and grinding operations. The Production



Fig. 1 Spauger bit, by Milwaukee Tool®

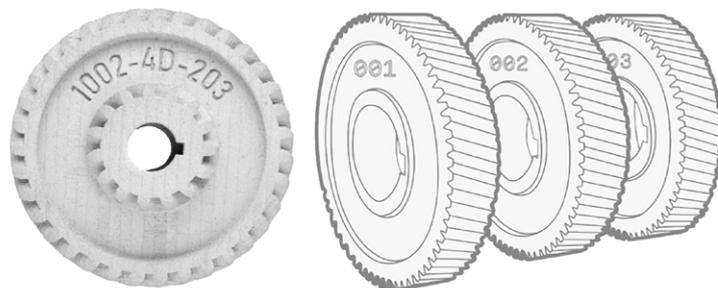


Fig. 2 An example of mass customisation using Binder Jetting technology

System has reduced the number of steps in spauger manufacturing from more than twenty steps to four and makes it possible to produce as many as 1,400 spauger bits per four-hour build.

**Mass customisation**

The Production System is capable of mass customising batches of generatively designed gears to various degrees with mass production efficiency. Instead of needing to post-process each part using laser or electrochemical etching, ink marking, or dot peening, parts can now be printed with serial numbers – or other customisation details – in place, rendering an entire build volume of unique parts with no need for post processing.

**Pre-assembled hinge**

Standard hinge designs, such as those used in spectacles, typically consist of two leaves that are



Fig. 3 A pre-assembled eyewear hinge prototype

bound by, and revolve around, a central pin. Assembly of these small components can be time-consuming in high volumes, and often requires precision engineering tools and equipment to manufacture. The Production System is able to print more than 45,000 pre-assembled 12

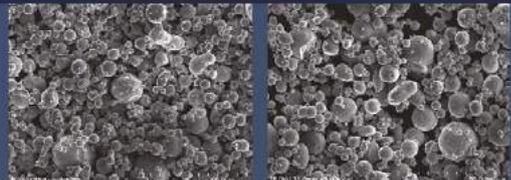
x 5 x 6 mm spectacle hinges in a single four-hour build. The hinge featured at Formnext was manufactured with the pin built directly into the knuckle of the mating leaf – eliminating assembly time and reducing the risk of disassembly with use over time. [www.desktopmetal.com](http://www.desktopmetal.com) ■



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## Heraeus and Engel partner on the injection moulding of amorphous metals

Injection moulding machine manufacturer Engel Austria GmbH, Schwertberg, Austria, and technology company Heraeus, Hanau, Germany, have partnered on the production and processing of amorphous metals by injection moulding. Heraeus reports that it has developed a new range of amorphous metal alloys under the name 'Amloy' and is using an Engel injection moulding machine to process them.

By injection moulding amorphous metals, cycle times are said to have been reduced by up to 70%, making possible the fully automated large series production of finished products with characteristics not previously achievable. As a result, the companies stated that amorphous metal parts could see application in new fields such as the automotive, aerospace, medical technology, industry, lifestyle and electronics sectors.

In contrast to pure metals and conventional alloys, amorphous metals are characterised by an irregular, non-crystalline structure. This makes them both extremely hard and highly elastic. They are also exceptionally resilient, corrosion-resistant and biocompatible according to ISO 10993-5.

Heraeus's new Amloy product range consists of zirconium-based alloys and copper-based materials, with the use of copper allowing for low unit prices and a broad spectrum of potential applications. The company stated that it is currently developing Amloy alloys based on titanium, iron and platinum.

Engel stated that it has developed a new hydraulic injection molding machine specifically for the processing of Amloy. Especially in terms of the injection process, this machine is said to differ from a conventional injection moulding machine for plastic or MIM processing.

A special focus of its development was on the even heating of the Amloy blanks. Depending on size and geometry, in a single work step, one or more ready-to-use parts with a very high surface quality is produced within 60–120 seconds, with no manual post-processing required.

The companies believe that this makes the injection moulding of Amloy superior to both conventional Metal Injection Moulding and CNC machining. The material composition and the fully automated production process from melting to the dynam-



*Engel and Heraeus have partnered on the production and processing of amorphous metals*

cally regulated injection procedure result not only in significantly reduced cycle times, but also reduce the required heating power by 40–60%, making injection moulding with amorphous metals more cost efficient.

Amloy alloys are said to be particularly suitable for precision components subject to heavy mechanical use, and for very high-quality decorative elements in the automotive, aerospace, medical technology, industry, lifestyle and electronics sectors.

In these applications, they can be used as a substitute for steel, titanium or technical plastics, which are chromium-plated in an additional work step after injection moulding. All Amloy materials and the injection moulding machines are offered free of licences.

[www.engelglobal.com](http://www.engelglobal.com)

[www.heraeus.com](http://www.heraeus.com) ■

## Sandvik reports record Q3 operating margin

Sweden's Sandvik Group has reported its financial results for the third quarter 2018. The company reported an order intake of SEK 24,192 million for the quarter, an increase of 9% compared to Q3 2017 (SEK 21,888 million). An adjusted operating margin of 18.9% was said to be a record high for a third quarter.

Adjusted operating profit for Q3 2018 was reported at SEK 4,587 million, an increase of 37% compared to Q3 2017 (SEK 3,338 million). Earnings for the quarter were said to have been positively impacted by

a net capital gain of SEK 618 million, generated by the divestment of Sandvik Hyperion. Excluding positive effects from changed exchange rates, structure and metal price effects, the adjusted operating profit improved by 25%.

Order intake and revenues in the third quarter improved organically by 9% and 10% respectively, with a reportedly strong contribution from all three business areas. Sandvik Materials Technology reported an increase in orders of 22%, while orders for Sandvik Mining and Rock

Technology increased organically by 8% and Sandvik Machining Solutions also reported an organic order growth of 8%.

Björn Rosengren, President and CEO of Sandvik Group, stated, "In the third quarter, order intake improved significantly in all three business areas on the back of strong progress in most customer segments and in the three major geographical regions. [...] I am also pleased that we made progress on reshaping the business portfolio toward improved long-term sustainable value creation as we closed a number of acquisitions and completed earlier-announced divestments."

[www.home.sandvik](http://www.home.sandvik) ■



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## Liberty Powder Metals secures £4.6 million for metal powder atomisation project

Liberty Powder Metals, Sheffield, UK, a subsidiary of Liberty House Group, has secured £4.6 million in funding from the Tees Valley Combined Authority Cabinet, UK, to support its acquisition of a vacuum atomisation system for the development and manufacturing of speciality alloy metal powders for use in industries such as Metal Injection Moulding and metal Additive Manufacturing. The overall cost of the scheme is £9.83 million, with almost £4 million having been invested by Liberty and the CASCADE project.

The project will be based at the Materials Processing Institute in South Bank, Middlesbrough, UK, a not-for-profit research and innovation centre which supports industry to develop new materials, processes and technologies. As there are currently said to be only two such atomisers in the UK, the system will be set up on an open access basis to enable collaborative research programmes.

Jon Bolton, Chief Executive of Liberty Steel UK, commented, "As a group, we are committed to revitalising

the metals and engineering industry through innovation and we're very proud to partner with the Tees Valley Combined Authority and the Materials Processing Institute to take forward a game-changing technology that will build a bright new future for these sectors in the UK and worldwide."

Chris McDonald, Chief Executive Officer of the Materials Processing Institute, added, "The Institute can bring a high level of scientific expertise to this project with our capabilities in advanced materials and we are delighted to support Liberty in the next phase of its powder metals project, which is essential for the continued development and refinement of Additive Manufacturing processes."

In 2017, Liberty Speciality Steels (then Tata) reported that it had identified metal powder production as a key strategic future product range in the sectors of oil & gas, automotive and aerospace, a view upheld by the new leadership team. Under CASCADE, the company plans to establish a medium-term development programme to construct a large-scale atomising facility with annual production capacity of 400 tonnes per year, with a planned increase to 1200 tonnes annually.

[www.libertyhousegroup.com](http://www.libertyhousegroup.com)

[www.mpiuk.com](http://www.mpiuk.com) ■



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## Pfeiffer Vacuum opens new North American headquarters

Pfeiffer Vacuum, Aslar, Germany, a provider of high-tech vacuum solutions for the semiconductor, industrial, coating, analytical and R&D markets, recently opened its new North American headquarters, a 2,508 m<sup>2</sup> building in Nashua, New Hampshire, USA. This will be the company's base for administration, sales, product management, marketing and customer care.

In addition, the company's former administration building has been converted into a Service Center of Excellence, bringing together all service activities for the major part of the Pfeiffer Vacuum product portfolio. State-of-the-art automated cleaning and test equipment is to be employed at the centre, said to result in high-quality, rapid repairs to the highest standards.

Together with the company's service center in Austin, Texas, USA, Pfeiffer Vacuum stated that it now offers an ideal organisational structure to serve its North American customers. Daniel Saelzer, President of Pfeiffer Vacuum Inc., commented, "With the completion of the two facilities, Pfeiffer Vacuum will be able to better support our valued customers throughout North America, while at the same time providing a modern, best-in-class work environment for our staff."

[www.pfeiffer-vacuum.com](http://www.pfeiffer-vacuum.com) ■

## EPMA Fellowship Award Winners named at Euro PM2018

The European Powder Metallurgy Association (EPMA) announced the recipients of its second annual Fellowship Award at Euro PM2018, held in Bilbao, Spain, October 14-18. The EPMA 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 2018 Fellowship Awards were:

### **Prof Paul Beiss, IWM – RWTH Aachen, Germany**

Prof Paul Beiss is a Graduate of Mechanical Engineering from RWTH Aachen, where he studied with a focus on production engineering until 1972, writing his doctoral thesis on copper extrusion. He became a professor for metallic materials in mechanical engineering at RWTH Aachen in 1994.

Beiss is a Fellow of the American Powder Metallurgy Institute and has been active with the EPMA since 2004, especially within the EuroPress&Sinter sectoral group and RET working group.

### **Prof Dr Herbert Danninger, Technische Universität Wien, Vienna, Austria**

Prof Dr Herbert Danninger completed his doctoral thesis, titled 'Influence of the Manufacturing Parameters on the Properties of Tungsten Heavy Alloys', at the Institute for Chemical Technology of Inorganic Materials in 1980. He was appointed as a full professor for chemical technology of inorganic materials in 2003.

In January 2016, Danninger was awarded the Doctor honoris causa of Universidad Carlos III de Madrid, Spain. He has been active with



*Prof Paul Beiss (top) and Prof Dr Herbert Danninger (below) accept the 2018 EPMA Fellowship Award (Photos © Andrew McLeish Euro PM2018)*

the EPMA since 2004, within the EuroHIP, EuroMIM, EuroAM and EuroHM sectoral groups and the EPMI working group.

[www.europm2018.com](http://www.europm2018.com) ■



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## Patrick J McGeehan joins AMP Board of Directors

Patrick J McGeehan has joined the Board of Directors of Advanced Metal-working Practices, LLC (AMP), Carmel, Indiana, USA, a producer of feedstock and provider of related services for the Metal Injection Moulding industry.

In addition to his new appointment to the board of AMP, McGeehan is currently a member of the board of the Metal Powder Industries

Federation (MPIF) and served as its president from 2015-2017. He has previously held leadership positions at both Hoeganaes Corporation and Ametek, Inc.

Dan Rechter, Board Chair at AMP, stated, "Pat brings forty years of experience in the metal powder industry, as well as excellent industry knowledge because of his

involvement with the Metal Powder Industries Federation... I know Pat will be a very valuable part of AMP's board for years to come."

"I look forward to working with the AMP Board to help Lane Donoho, AMP's General Manager, be successful in carrying out the company's strategic mission, while continuing to provide its customers with the highest level of quality and service in the industry," stated McGeehan.

[www.amp-llc.net](http://www.amp-llc.net) ■



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## Linde and Praxair successfully complete merger

Linde plc, Guildford, UK, has successfully completed the merger between Praxair and Linde AG announced in December 2016. The combined company has adopted the Linde name and will be listed on both the New York Stock Exchange (NYSE) and the Frankfurt Stock Exchange (Prime Standard segment).

Now that the business combination has been completed, the companies stated that they will focus on finalising the divestitures required by the respective antitrust authorities. Necessary divestitures include, in particular, certain sales in the United States, which Linde AG is required to complete by January 29, 2019. Until the completion of the majority of such divestitures, Linde AG and Praxair are obliged to operate their businesses globally as separate and independent companies and not coordinate any of their commercial operations.

The combined company will be governed by a single Board of Directors with equal representation from Linde and Praxair. Linde's Supervisory Board Chairman, Prof Dr Wolfgang Reitzle, was expected to become Chairman of the new company's board, while Praxair's Chairman and CEO, Steve Angel, was expected to become CEO.

[www.linde.com](http://www.linde.com)

[www.praxair.com](http://www.praxair.com) ■

## Short course on Atomisation for Metal Powders set to run in 2019

Atomising Systems Ltd and Personal Development Advanced Courses (PERDAC), a division of CPF Research Ltd, will hold their popular short course on atomisation for metal powders for the twelfth time in 2019. The two-day course will take place from March 14-15 in Manchester, UK.

The course will consist of presentations from John Dunkley (Chairman, Atomising Systems Ltd), Dirk Aderhold (Technical Director, Atomising Systems Ltd), Tom Williamson (Research Engineer, Atomising Systems Ltd), Rajeev Dattani (Applications Specialist, Freeman Technology) and Andrew Yule (Emeritus Professor, University of Manchester).

[www.atomising.co.uk](http://www.atomising.co.uk) ■

## 2020 Powder Metallurgy World Congress heads to Montréal

The 2020 edition of the World Congress on Powder Metallurgy & Particulate Materials (WORLDPM2020) will be held in Montréal, Quebec, Canada, from June 27–July 1, 2020.

The congress will be organised by the Metal Powder Industries Federation (MPIF) and APMI International in conjunction with Additive Manufacturing with Powder Metallurgy (AMPM) 2020 and the Tungsten, Refractory and Hardmaterials Conference 2020.

The congress will cover the full range of Powder Metallurgy topics, ranging from metal powder production and technology, powder compaction, sintering and post-processing, to Metal Injection Moulding, cemented



WORLDPM2020 will be held in Montreal, Canada (Photo courtesy David Iliff)

carbides, porous materials, Additive Manufacturing and the design and simulation of Powder Metallurgy parts.

In addition to the congress programme, there will be a major exhibition featuring a wide range of international exhibitors and providing an opportunity for networking with material and equipment suppliers, part producers and end-users.

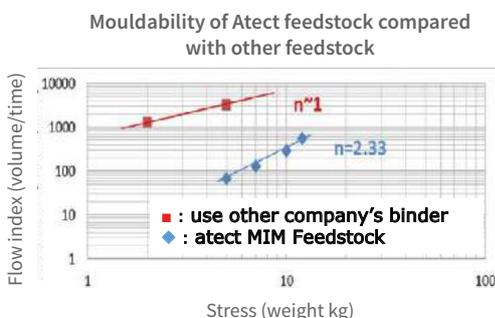
WORLDPM is held every two years and in 2018 took place in Beijing, China.

[www.mpif.org](http://www.mpif.org) ■

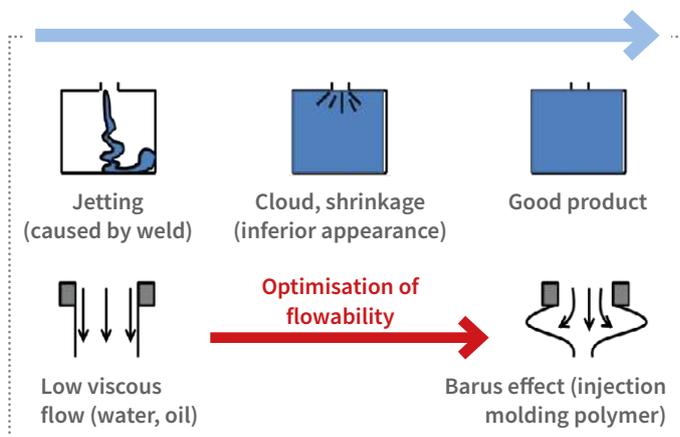
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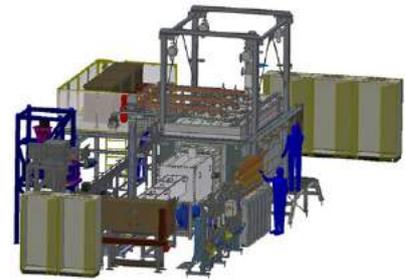
## EU-funded CARBIDE2500 project to develop first 2500°C industrial furnace

Cremer Thermoprozessanlagen GmbH, Düren, Germany, has received EU funding for its CARBIDE2500 project to develop the first 2500°C industrial furnace. The project launched in May 2018 and is expected to conclude by the end of April 2020, with the total cost being reported at €1,331,000, of which the EU has contributed €931,700 through its Horizon 2020 research and innovation programme.

Cremer specialises in pusher furnace systems with graphite coatings which operate at extremely high temperatures, above 2000°C. These systems are used in the carburising process for carbide powders such as tungsten carbide (WC). According to the company, the economic downturn and subsequent recovery in Europe

has seen increasing demand for higher strength materials which offer longer product lifespans and higher overall performance, allowing for lower operational costs.

Tungsten carbide is used in many different applications across multiple large industrial sectors, including automotive and aerospace manufacturing, construction, surface and underground mining, oil & gas exploration, as well as in many manufacturing industries (including paper, textiles, electronics, etc). As a result of increasing demand, the global tungsten carbide powder market is expected to grow from €13.6 billion in 2016 to €22.91 billion in 2026, at a compound annual growth rate of 5.4%. Demand for other carbides, such as tantalum



carbide or niobium carbide, is also increasing. Tests have proven that WC powder produced at 2500°C is three-to-five times higher strength than the same material produced at 2200°C. However, there are currently no industrial scale furnaces capable of operating at 2500°C.

The CARBIDE2500 furnace will be the first industrial furnace capable of operating at 2500°C, thereby making it possible to produce higher strength carbides than currently possible.

[www.cremer-polyfour.de](http://www.cremer-polyfour.de) ■



### Adopting Chinese advanced gas and water combined atomization technology

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17-4PH	4.70	0.34	7.70
304L	4.80	0.34	7.80
HK30	4.70	0.35	7.70
4J29	4.90	0.36	7.95

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## Innovnano reports results of fracture toughness tests on its 2YSZ structural ceramic powder

Innovnano, Coimbra, Portugal, a manufacturer of structural zirconia ceramics, has reported the results of fracture toughness tests on its Innovnano 2 mol.% Yttria-Stabilised Zirconia (2YSZ) structural ceramic powder using the single edge pre-cracked beam (SEPB) method with the Japan Fine Ceramics Center, Nagoya, Japan.

The results reported show that 2YSZ has outstanding fracture toughness, combined with high flexural strength and ageing resistance for physically demanding structural ceramic applications. With a value of 7.2 MPa.m<sup>1/2</sup>, the fracture toughness of 2YSZ was said to far exceed the current structural ceramic of choice, 3YSZ, which has a fracture toughness of just 4.2 MPa.m<sup>1/2</sup>.

Innovnano produces 2YSZ using Emulsion Detonation Synthesis (EDS), its proprietary technology for the high-volume, high-quality production of nanostructured powders. This technology produces powders with a nanostructure that provides improved structural properties such as hardness, fracture toughness, flexural strength and resistance to thermal shock.

The material is said to combine all the desired properties of 3YSZ, with the added benefit of improved fracture toughness inherent in lower yttria content YSZs.

Previously, the fracture toughness of Innovnano has been investigated using traditional indentation methods (IF) that demonstrated a fracture toughness value above 15 MPa.m<sup>1/2</sup>. This is significantly higher than the value for 3YSZ benchmark, which was found to be just 5 MPa.m<sup>1/2</sup> using the same method.

To further qualify the outstanding fracture toughness of 2YSZ, additional tests have recently been conducted using a different measurement technique. The single edge precracked beam (SEPB) method (ISO 15732:2003) is recommended for fine grain ceramics to provide a more accurate representation of a material's fracture toughness.

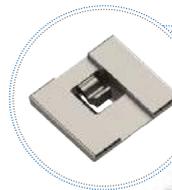
Results from the study conducted at the Japan Fine Ceramics Center confirmed the fracture toughness of 2YSZ (7.2 MPa.m<sup>1/2</sup>) to exceed that of 3YSZ benchmark (4.2 MPa.m<sup>1/2</sup>), further demonstrating the superior properties of Innovnano 2YSZ over other ceramic materials.

André de Albuquerque, Innovnano CEO, commented, "The fracture toughness of Innovnano 2YSZ powder is exceptional. Confirmed by two different measurement techniques to exceed that of 3YSZ, while maintaining its other desirable properties, it offers an exciting structural ceramic alternative."

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## Kymera International sold to Palladium Equity Partners

Palladium Equity Partners, LLC, New York City, USA, a private investment firm with over \$2.5 billion in assets under management, has announced that one of its affiliated private equity funds has acquired global speciality materials company Kymera International (the collective of ACuPowder International, ECKA Granules and SCM Metal Products), from Los Angeles-based private investment firm Platinum Equity. The terms of the transaction were not disclosed.

The Kymera group of companies produces a variety of speciality materials, powders, pastes and granules used in a wide range of metallurgical, chemical and industrial processes, including Powder Metallurgy, metal Additive Manufacturing and Metal Injection Moulding. Many of the company's products are custom-developed for specific customer applications in a variety of end-markets, including chemical, speciality auto, general industrial, mining and aerospace, among others.

The group is headquartered in Durham, North Carolina, USA, and has global production capabilities across the United States, Australia, China, Europe and the Middle East. Under Platinum Equity's ownership, it saw significant growth from two copper powder plants to become one of the largest manufacturers of speciality aluminium and copper powders worldwide.

"Kymera's success reflects the culmination of a strategy to acquire multiple speciality material companies across the globe and integrate them operationally under one brand," said Jacob Kotzubei. "Starting with the carve out of SCM Metal Products, we partnered with management to build on the platform over time and supported the company's organic growth through investments in R&D and deployed our M&A&O® resources to source and execute three add-on acquisitions. The result is a high-performing, well-diversified business with a dynamic leadership team led by Barton White."

Palladium stated that it is backing the Kymera management team with the goal of pursuing various avenues of growth, including accelerating the expansion of the company's value-added product portfolio and pursuing complementary acquisitions in the speciality materials industry. Adam Shebitz, a Managing Director of Palladium, commented, "Barton and the rest of the Kymera leadership team have built a leading specialty materials manufacturer with a reputation for delivering excellent service, deep technical expertise and complete reliability to its customers. We are excited about Kymera's next chapter of growth."

Barton White, Kymera CEO, added, "We are proud of the results we have achieved under Platinum, and thank them for their support over their ownership period. We look forward to working with Palladium and leveraging their industry experience to accelerate our expansion plans, while continuing to focus on serving our customers as their trusted partners."

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[www.palladiumequity.com](http://www.palladiumequity.com)  
[www.platinumequity.com](http://www.platinumequity.com) ■

## Arcast to supply large-scale research gas atomiser to CEIT

Arcast Inc., Oxford, Maine, USA, is to supply a large-scale research inert gas atomiser to the Centro de Estudios e Investigaciones Técnicas de Gipuzkoa (CEIT), San Sebastián, Spain. CEIT is a non-profit research centre and carries out applied industrial research projects under contract, working closely with clients' R&D departments.

The Materials and Manufacturing division at CEIT includes Powder Metallurgy research, and is currently expanding its capabilities to develop new alloy powders for metal Additive Manufacturing, Metal Injection Moulding and other Powder Metallurgy markets. It belongs to the IK4 Research Alliance, a collective

of seven research institutes from Spain's Basque Country, and also has ties with Spain's Tecnum School of Engineering, Germany's Fraunhofer Society, and other R&D institutions and research centres globally.

The new atomiser will allow the use of various atomising geometries to produce complex alloys in batches of 50–250 kg. These features are said to offer a good capacity and capability to address the growing needs of the metal powder market. Arcast stated that it hopes to work with the team at CEIT to create larger quantities of advanced metal powders in the future.

[www.ceit.es](http://www.ceit.es)  
[www.arcastinc.com](http://www.arcastinc.com) ■

## Wittmann merges its businesses into a single company

The Wittmann Group, headquartered in Vienna, Austria, a producer of injection moulding machines, robots and peripheral equipment for industry, has announced that it will merge its two main divisions – Wittmann Battenfeld GmbH & Co. KG, Meinerzhagen, Germany, and Wittmann Robot Systeme GmbH, Nuremberg, Germany – into a single company. The merged company will trade as Wittmann Battenfeld Deutschland GmbH and be headquartered in Nuremberg.

[www.wittmann-group.com](http://www.wittmann-group.com) ■

## EPMA reflects on Euro PM2018 and reports growth in AM participation

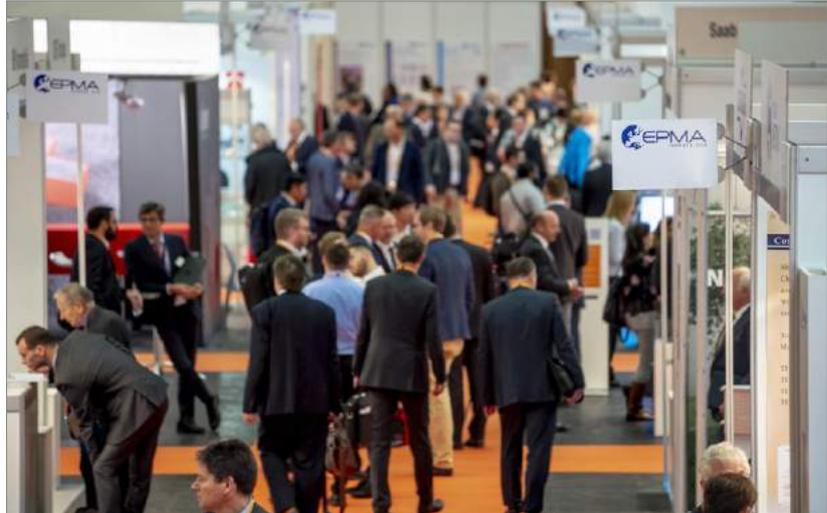
The European Powder Metallurgy Association (EPMA)'s Euro PM2018 Congress & Exhibition was held in Bilbao, Spain, from October 14–18, 2018. The event once again attracted a wide range of participants from the international Powder Metallurgy industry to discuss the latest trends and technological innovations.

According to the EPMA, this year's event drew participants from more than fifty countries in Europe and the rest of the world. Over three-hundred oral and poster presentations were given during the event, and more than 1,100 participants attended the conference and exhibition, where over one-hundred booths hosted exhibitors from across the PM supply chain.

Speaking on the event's success, Dr Olivier Coube, EPMA Technical Director, stated, "Euro PM2018 represents a turning point of our annual congress and exhibition in terms of size, with 50% more presentations vs 2017, including a 40% increase in metal Additive Manufacturing content, and at the same time an enlarged programme for conventional PM technologies, which remain the backbone of our industry."

"I would like to especially acknowledge the work of the EPMA staff as they have made this change of dimension logistically possible," he continued. "[Holding this event] one month after the World PM event was a risk, it was hard work but at the end it was a success with approximately 20% more delegates than last year."

Lionel Aboussouan, EPMA Executive Director, added, "Bilbao was a great location and made for a thriving event. The enlarged technical programme and extended exhibition opening times helped to attract a diverse range of companies and sectors that want



*Delegates in the Euro PM2018 exhibition (Photo © Andrew McLeish Euro PM2018)*

to learn more about what PM can do for their applications and industries. We would like to thank all the EPMA supporters and stakeholders who have assisted in making this event a success."

For the fifth year, Euro PM2018 hosted the EPMA's Young Engineers Day, which enabled students from five universities to attend the event for an intensive two-day programme and gain an understanding of what a career in the PM industry can offer. Euro PM2018 gave the opportunity for each of the EPMA's Sectoral Groups to hold their meetings alongside the technical sessions. The metal Additive Manufacturing group, EuroAM, celebrated its five-year anniversary during the event, with a well-attended session on new and innovative AM-related processes, a review of the past and future works and challenges for the group, and the third Metal AM Trends Survey.

The hardmetals group, EuroHM, invited keynote speakers to give an update of the growing Spanish hardmetals community, while the press & sinter group, EuroPress&Sinter, used its session for a discussion on possible ways to improve the technology and the relationship between industry and academia. The Hot Isostatic Pressing group, EuroHIP, and Metal Injection Moulding group, EuroMIM, also met during the event.

In addition, a new functional materials group, EuroFM, was established as a result of the EPMA's 2018 Functional Materials seminar held in Jülich, Germany, earlier in the year, with the aim of representing materials that are used in functional applications such as electric cars and battery systems.

The technical programme also included a number of special interest seminars on the following topics:

- Additive Manufacturing: Success Case Studies in Production and Future Preview of Metal AM
- Hard Materials: Micromechanical Testing of HM
- Hot Isostatic Pressing & Additive Manufacturing: HIP and Heat Treatment of AM Parts – Microstructure and Mechanical Properties and the Effect of Combined HIP and Heat Treatment Cycles Compared to Conventional Processing
- Metal Injection Moulding: Quality and Tolerances of MIM components & Functional Materials: Soft and Hard Magnetic Materials
- PM Structural Parts: A Critical Analysis of the Press & Sinter Technology

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## AMT announced as a winner in EPMA 2018 PM Component Awards

During its Euro PM2018 Congress and Exhibition, Bilbao, Spain, October 14–18, 2018, the European Powder Metallurgy Association (EPMA) revealed the winners in its 2018 Powder Metallurgy Component Awards. The awards are open to all who manufacture components using powder metallurgical processes and the 2018 award consisted of the following component categories:

- Metal Injection Moulding (MIM)
- PM Structural (including Hard Materials and Diamond Tools parts)
- Additive Manufacturing
- Hot Isostatic Pressing (HIP)

The award for a metal injection moulded component was presented to AMT PTE Ltd, Singapore, for its one piece nozzle for automotive applications. The judges stated that the MIM nozzle featured a good finish with complex internal channels and was manufactured in a sustainable and economical way. The product was said to have opened up an entirely new application for MIM process capability, and AMT stated that it was the most complex part that it has produced to date.

Development efforts for the component focused on controlling the distortion of the plastic inserts during MIM, as the high injection pressure and temperature could greatly affect the insert integrity. The challenge was to maintain

a high packing pressure in the inner core channel, as any loss in pressure could lead to weakness and result in cracks.

Identifying the ideal injection parameters for a good overall part was said to be highly challenging. In addition, the tip of the nozzle, the diameter of the hole and the gap surrounding it were all controlled in the micron range, and produced using MIM without secondary operations. These critical features were achieved to a high definition.

The one piece nozzle is applied in a Selective Catalytic Reduction (SCR) system for commercial vehicles in Europe to comply with the Euro 5 and Euro 6 standards. Urea is connected to the centre

through the hole, and compressed air connected to the other channel. The compressed air is then pumped into the nozzle, exiting through the ring at the nozzle tip. This generates a low-pressure region at the tip, producing a venturi effect which draws the urea from the middle channel and sprays it onto the SCR system, reducing the exhaust  $\text{NO}_x$  to  $\text{N}_2$  and  $\text{H}_2\text{O}$ .

The undercut internal channel of the part can reportedly only be produced using AMT's patented In-Coring™ technology and is thus specially designed for MIM processing. Compared to the production of a similar part of a corresponding quality and finish by conventional machining and brazing, AMT reported a reduction in costs of up to one third.

[www.componentawards.epma.com](http://www.componentawards.epma.com) ■



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## SimpaTec reports on a successful Molding Innovation Day in Germany

Simulation and technology consulting company SimpaTec, Aachen, Germany, held its MiDay (Molding Innovation Day) on September 18, 2018, at the Stadthalle Balingen, Germany. The event was attended by more than two-hundred invited participants and hosted a range of discussion on the latest innovations in tool and mould making, providing an extensive overview of and insights into the potential of what the company refers to as 'future-oriented manufacturing processes.'

Commenting on the event, Christoph Hinse, SimpaTec's General Manager, stated, "It's just the right combination of theory and practice – subject-specific technical contributions, additional information in the exhibitor area – and enough space

and scope for direct discussions and clarifications of open questions."

"The personal contact and communication between the interested parties, exhibitors and speakers is particularly important to us," he continued. "Therefore, we are extremely pleased about the lively interactions which took place throughout the entire event. The positive feedback from the circle of attendees shows us that our MiDay Germany 2018 offered exactly the right balance between content, discussion and exchange of information on the subject of innovative tool making."

A broad range of information and suggestions on how to practically master everyday professional challenges was offered during the

event. The lecture programme looked at both the future and current use of future-oriented technologies in tool and mould making, with a number of speakers addressing current issues facing injection moulding.

Topics covered included how to make the right decisions for optimum mould temperature control, how to optimally operate cooling and temperature control circuits, how to optimise technology and costs in tool design, and the benefits of simulation analysis and tool evaluation.

The accompanying exhibition area saw a number of key companies in the industry present their latest technology and solutions, while giving attendees the opportunity to engage in discussions related to the programme content. The next MiDay Germany will take place on September 17, 2019, and will again be held at the Stadthalle Balingen.

[www.simpatec.com](http://www.simpatec.com) ■

## Lucideon appoints Anike Bütow its Technology and Strategic Leader

Development and commercialisation organisation Lucideon, Stoke-on-Trent, UK, which specialises in materials technologies and processes, has appointed Anike Bütow its new Technology and Strategic Leader. In the new role, the company stated that Bütow will be tasked with identifying opportunities in new markets, services and technologies by assessing global trends and their value, including global strategy assessments and the domestic and international expansion of the company.

Lucideon added that Bütow, who is based in Zurich, will bring an international perspective and a wide range of expertise to the role. Speaking five languages, she is a Certified Internal Auditor and registered dentist, with experience in finance and internal controls, dentistry in the public and private sectors and in the management of medical device clinical trials.

Speaking on her appointment, Bütow stated, "Lucideon is all about innovation and its business touches on so many industries and technologies. Our goal is to be the technical partner for emerging technologies and to be really at the forefront as a consulting partner for companies and organisations. The sky is the limit. We can touch on many aspects in the global marketplace and are in an exceptional position to expand the business globally."

In August, Lucideon announced a significant investment in new staff, systems, facilities and ventures in new markets, adding new laboratory space at its New York State facility and a £250,000 investment package in IT systems. The company now employs more than 240 staff around the world. Its global presence includes offices and laboratories in North and South Carolina, USA, New York, USA, and the Far East.



*Anike Bütow has been appointed Lucideon's new Technology and Strategic Leader (Courtesy Lucideon)*

The company also recently opened new offices in Switzerland and Austria and is planning to open sales offices in China, Japan and Korea. Near its headquarters in Stoke-on-Trent, it is supporting the National Advanced Sintering Centre (NASC) to fast-track advanced materials and materials processes into commercial products.

[www.lucideon.com](http://www.lucideon.com) ■



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## Worldwide smartphone shipments see 7% decline in Q3 2018

Components for smartphones account for a significant portion of Metal Injection Moulding production in China and Taiwan. The industry's producers and suppliers will therefore have been all too aware that worldwide smartphone shipments fell by 7% in the third quarter of 2018, according to a report by global technology market analyst firm Canalys. This was said to be the worst third quarter performance the industry has seen since 2015.

In China, the smartphone market shipped 100.6 million units, a year-on-year decline of 15.2% and sequential decline of 2.9%. India overtook the US as the second largest market, though both countries were said to have been hit by weaker seasonal performance compared with last year. Seven of the top ten markets recorded year-on-year declines reported to be caused by lengthening smartphone replacement cycles, worsening international trading conditions and competition from major Chinese vendors.

Fourteen of the top twenty smartphone brands in China were said to have declined in Q3 2018, putting pressure on vendors amid increasing component and labour costs. Chinese vendors are said to be highly focused on overseas expansion in South Asia, Africa and Central and Eastern Europe, to hedge against domestic business challenges, but it was stated that the current international trade environment and geopolitical issues will have a negative impact on business.

Greater China (including Hong Kong and Taiwan) was the worst performing region, down 14.6%

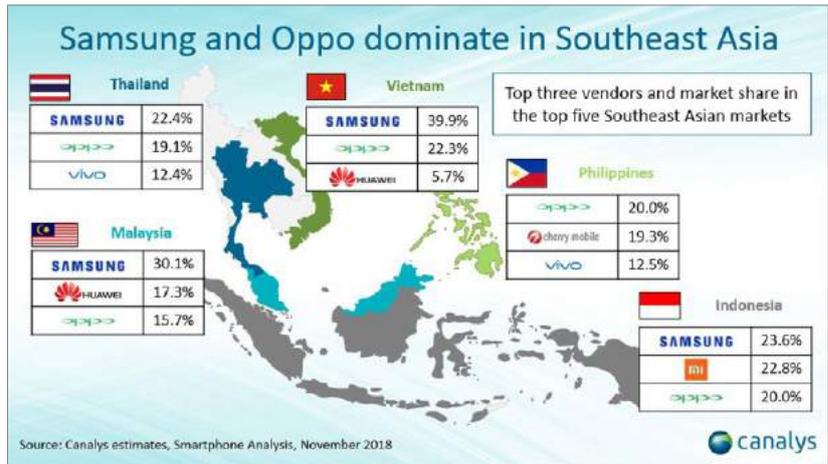


Fig. 1 In Southeast Asia, Samsung and Oppo have the highest market share (Courtesy Canalys)

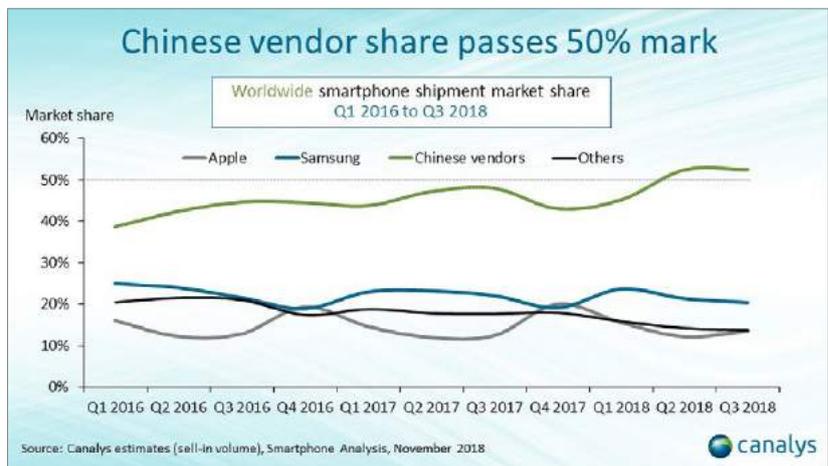


Fig. 2 China's smartphone vendors now account for more than 50% of global smartphone shipments (Courtesy Canalys)

annually. On the other hand, Central and Eastern Europe continued to be the top performer, growing 2.2% year-on-year, followed by Africa at 0.4%.

Samsung was the only vendor to post a year-on-year decline of 14%, reducing its market share to 20.4% from 22% in Q3 2017. Huawei took second place in the market ahead of Apple, shipping 52 million units after growing 33% year-on-year.

Apple grew by just 0.4%, shipping 47 million units. Xiaomi and Oppo rounded out the top five, shipping 33 million and 31 million units respectively. All Chinese vendors combined now account for

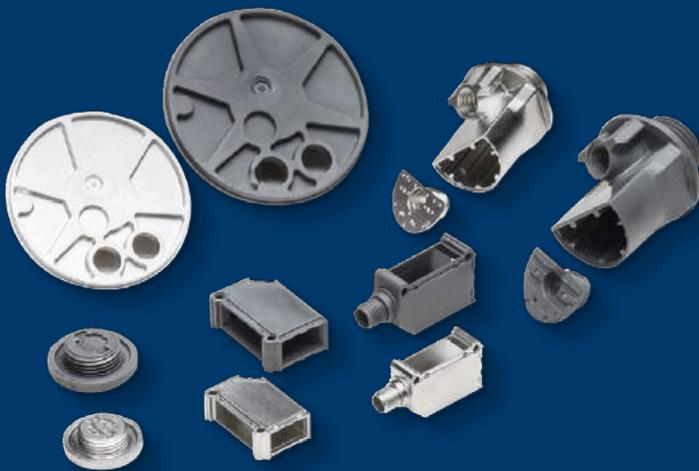
52% of the worldwide smartphone market, their highest share in history.

Apple's smartphone product transition is still underway, having launched its new flagship smartphones in September 2018. In ten days of availability in Q3, the iPhone XS shipped 3.3 million units, but was overtaken by the more expensive iPhone XS Max, which shipped 4.7 million units. China was the largest market for the iPhone XS Max, accounting for 45% of its shipments, while the US was its second largest market at 27%.

www.canalys.com ■

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## Highly porous Fe-2 wt.%P MIM parts produced using plasma-assisted debinding and sintering system

A furnace system developed in Brazil, which uses plasma and laminar gas flow to reduce cycle time in debinding and sintering, has been successfully used to produce metal injection moulded high porosity Fe-P-based alloys with good dimensional accuracy. In a paper published in *Materials Letters* (Vol. 231, 2018, 163-166), Natalia F Daudt and co-authors from the Universidade Federal de Santa Maria, Universidade Federal de Santa Catarina and Universidade Federal do Rio Grande do Sul, Brazil, report on their research into using the Plasma Assisted Debinding and Sintering (PADS) process to produce the highly porous sintered Fe-2 wt.% P MIM material, which they state has potential application for metallic scaffolds used for controlled drug delivery.

The soft magnetic Fe-P material is biodegradable, non-toxic and would allow controlled drug delivery using a magnetic field. Other potential applications for the porous MIM sintered Fe-P alloy would include electrochemical devices, such as current collectors for proton exchange membrane fuel cells, or as electrodes in modern Ni-Fe batteries.

The authors state that sintered Fe-2 wt.% P MIM parts can be produced with porosity as high as 58.6 vol.% and, on using PADS, there is good dimensional accuracy in the finished parts. Porosity distribution is homogeneous and mostly interconnected in the plasma sintered samples – an important factor for controlled drug delivery in metallic scaffolds.

For the MIM feedstock, the authors used an iron powder having a D90 particle size distribution between 45 and 150 µm, mixed with a Fe<sub>3</sub>P powder (16 wt.% P and particle size of 75 µm), and this mixture was blended with an organic binder consisting of 60 vol.% paraffin wax, 35 vol.% polyethylene and 5 vol.% stearic acid at a temperature of 150°C. Powder loading in the MIM feedstock was 50 vol.% and 53 vol.%. The feedstock was injection moulded into cylindrical parts of 30 mm diam. and 3 mm tall.

The moulded parts were immersed in an n-hexane bath to remove the paraffin wax and stearic acid. PADS was then performed in a low-pressure system by first heating up to 500°C at a rate of 1.6°C/min and then applying a short dwell time

of just 1 min to remove the residual binder. The heating rate was sufficient for fast binder removal but not leading to shape distortion of the samples. This compares with conventional thermal debinding in a resistive furnace using a heating rate of 1°C/min and dwell time of 120 min. Final sintering temperature varied from 800 to 1100°C using either argon or hydrogen atmosphere with a holding time of 2 hr. Table 1 gives the resulting porosity and shrinkage for the sintered Fe-P materials, including a reference sample, which was thermally debound and sintered in a resistive furnace under argon.

It was found that the MIM samples sintered using PADS had a significantly lower shrinkage and higher porosity than samples sintered in a resistive furnace. As expected, the sample with the higher powder loading in the feedstock resulted in lower porosity. All sintered samples showed the same phase composition. Fe-α (ferrite) was mainly the only observed phase, Fe<sub>2</sub>P and Fe<sub>3</sub>P decreased considerably. P atoms from Fe<sub>2</sub>P and Fe<sub>3</sub>P diffused into the Fe-α matrix forming a solid solution. Furthermore, X-ray diffraction results indicated that injection moulded Fe-2wt.% P parts did not form oxide, nitride or carbide compounds during PADS.

[www.journals.elsevier.com/materials-letters](http://www.journals.elsevier.com/materials-letters)

Contact: natalia.daudt@ufsm.br ■

Powder load (vol.%)	Sintering		Porosity (%)			Shrinkage in (%)	
	Atmosphere	Temperature (°C)	Open	Closed	Total	Height	Diameter
50	Ar resistive	1,100	9.7	6.8	16.5 ± 2.0	14.0 ± 3.5	16.7 ± 2.2
50	Ar plasma	900	47.1	11.5	58.6 ± 3.3	0.12 ± 0.5	0.25 ± 0.3
50	Ar plasma	1,000	44.5	5.0	49.5 ± 2.4	0.0 ± 0.7	0.27 ± 0.2
50	Ar plasma	1,100	38.4	6.4	44.8 ± 4.0	1.1 ± 0.5	0.54 ± 0.2
53	Ar plasma	1,100	33.9	3.9	37.8 ± 1.5	1.1 ± 0.3	0.90 ± 0.3
50	H <sub>2</sub> plasma	1,100	37.2	8.5	45.7 ± 0.6	2.2 ± 1.3	1.30 ± 0.3

Table 1 Resulting porosity and shrinkage of Fe-P porous parts in relation to sintering temperature and feedstock (From the paper 'Highly porous Fe-2wt% alloy produced by plasma assisted debinding and sintering of injection moulded parts' by N F Daudt, et al. *Materials Letters* Vol. 231, 2018 163-166)

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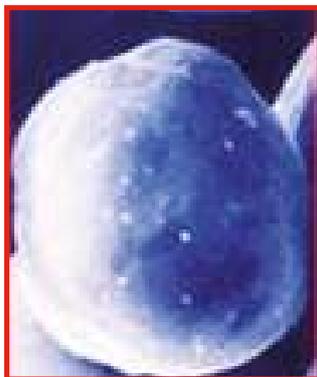
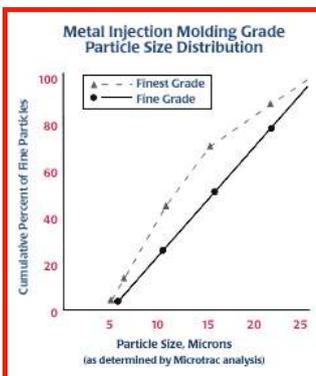
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## Hybrid water-gas atomisation process for lower cost MIM grade powders

As the demand rises for fine metal powders suitable for Metal Injection Moulding, so the challenges increase for powder manufacturers to develop atomisation techniques which not only produce the fine spherical powders required, but also at lower cost. Water atomisation has been the most common and economic method for high volume powder production, but the high oxidation and irregular shape achieved restricts its application range in MIM. Gas atomisation is frequently used to produce powders having spherical shape, high purity and low oxygen content, but gas consumption is high and the yield of fine powder is often low.

A paper by Zhu Jie, *et al*, published in *Frontiers of Materials Processing, Applications, Research*

*and Technology*, 2018, pp 391-397, describes the development of an improved hybrid atomisation technique which, the authors state, combines the advantages of gas and water atomisation. Research to develop the hybrid system took place at the Guangdong Institute for Materials and Processing, in Guanzhou, China, and the authors state that the most important feature of the hybrid system is that it can produce a high yield of atomised fine powders having good sphericity at low cost.

The apparatus developed for hybrid atomisation uses an annular gas nozzle (cone nozzle) and four symmetrical discrete high-pressure water jet nozzles (V-jet nozzles), as can be seen in Fig. 1. The authors used 316L stainless steel for

atomisation experiments with the molten metal fed through a 4 mm diameter hole in the bottom of the tundish.

The flow of molten metal from the tundish increases as the high-pressure water ejected from the V-jet nozzles and the large amount of atomising gas is sucked into the chamber to create a negative pressure zone. Gas pressure is constant at 5 MPa and the super high-pressure water is up to 120 MPa. The authors reported that the difference in the water pressure of the V-jet nozzles, due to the two different apex angles used, delays the solidification of the molten droplets in the first atomisation stage and thereby produces powder with a higher degree of sphericity. The secondary atomisation by the high-pressure water is said to achieve the desired fine particle size. The resulting atomised 316L stainless steel was dewatered followed by vacuum drying.

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Number	Pressure of water (MPa)	Water flow (W), L/min	Metal flow (M), kg/min	W/M ratio	Median particle diameter (D50)	Oxygen content ppm	Tap density g/cm <sup>3</sup>	Yield %
1	70	41.41	7.11	5.82	18.05	4089	4.85	48.51
2	85	45.63	7.27	6.27	16.10	4533	4.80	57.50
3	100	49.50	8.89	5.56	9.91	4232	4.78	70.70
4	110	51.91	9.10	5.70	9.17	3832	4.75	73.40
5	120	54.22	10.19	5.32	8.48	3341	4.71	78.90

Table 1 Experimental atomisation parameters and results (From the paper 'Characterisation of Fine Metal Powders produced by Hybrid Water-gas Atomization for Metal Injection Molding' by Zhu Jie, et al, *Frontiers of Materials Processing, Applications, Research and Technology*, 2018, pp 391-397)

As can be seen in Table 1, there is a strong dependence on water pressure of the median particle size (D50) achievable in the hybrid atomisation system. At 120 MPa water pressure, a yield of nearly 79% is possible for a D50 of 8.48 µm. Tap density is a measure of good sphericity in the powders and all values obtained in the hybrid atomisation process were over 4.7 g/cm<sup>3</sup>. The authors state that whilst the initial results of using

this improved hybrid gas/water atomisation process are encouraging, work is ongoing to further improve properties and, in particular, to reduce the oxygen content, which, at 3341 ppm, is still significantly higher than in pure gas atomised 316L stainless steel powders.

Contact: zhujie20070318@163.com ■

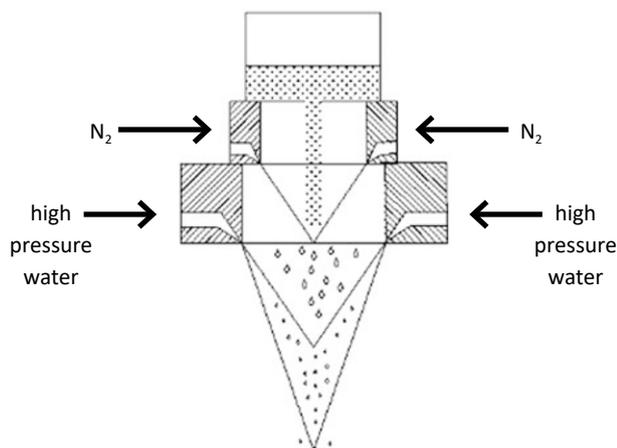


Fig. 1 Design of the improved hybrid gas and water atomisation apparatus used to produce fine, spherical stainless steel powders. (From the paper 'Characterisation of Fine Metal Powders produced by Hybrid Water-gas Atomization for Metal Injection Molding' by Zhu Jie, et al, *Frontiers of Materials Processing, Applications, Research and Technology*, 2018, pp 391-397)

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## Micro-sized piezoelectric structure produced by Powder Injection Moulding

Piezoelectric structures made from  $\text{Pb}(\text{Mg},\text{Nb})\text{O}_3\text{-Pb}(\text{Zr},\text{Ti})\text{O}_3$  [PMN-PZT] ceramics are widely applied as components for sensors, actuators and transducers used in smart structures because they can directly convert mechanical energy to electrical energy, and vice versa. A number of manufacturing techniques such as dice-and-fill, casting, embossing and micro pressing can be used to produce the piezoelectric structures.

Powder Injection Moulding is also considered to be a candidate process thanks to its ability to produce in large volumes piezoelectric structures having uniform pattern shape, and a paper recently published in *Ceramics International* (Vol. 44, 2018, pp 12,709-12,716), reports on the successful development of a PIM process to produce micro-sized structures having a high aspect ratio.

Jae Man Park and co-authors from the Pohan University of Science and Technology (Gyongbuk, Korea), the Agency for Defence Development (Daejeon, Korea) and the University of Louisville (Kentucky, USA), stated in the paper that, whilst PIM has already

been used to produce piezoelectric structures in millimetre scale, using the PIM process to produce pattern sizes in micro-scale with high aspect ratios presents new challenges, particularly in demoulding from metal mould inserts.

To overcome demoulding problems, the researchers introduced a Separated Mould System (SMS) with two parts to replicate a micro-sized structure with a high aspect ratio. The separated mould was fabricated using optimised X-ray micro-machining and has a diameter of  $190\ \mu\text{m}$  and height of  $1000\ \mu\text{m}$  (Fig. 1). The separated mould allows demoulding to be carried out more easily because it is done in the horizontal direction, which does not damage the structures.

The feedstock used to produce the micro-size piezoelectric structures involved mixing a PMN-PZT powder having D50 particle size of  $1.21\ \mu\text{m}$ , with a multiple component binder containing paraffin wax, carnauba wax, microcrystalline wax, polypropylene and stearic acid. Mixing was done three times at  $140^\circ\text{C}$  and a mixing speed of 150 rpm. Multiple mixing was found to lead to higher homogeneity of the

feedstock and had a positive effect on mould filling. Optimal powder loading in the feedstock was 52 vol.%. Injection moulding was done by placing the separated mould on the base mould and injecting the feedstock into the micro-cavity at a mould temperature of  $65^\circ\text{C}$ , injection temperature of  $160^\circ\text{C}$  and velocity of  $140\ \text{mm/s}$ . Injection velocity was found to be a key factor to achieve complete filling in micro-scale.

After the micro-scale green parts were demoulded from the separated mould without fracture, they were subjected to optimised debinding conditions, based on the thermal decomposition behaviour of the binders and lead (Pb) loss measured by thermogravimetric analyser (TGA), followed by sintering using conditions established in previous research on PIM of piezoelectric materials. Fig. 2 shows a sintered micro-sized piezoelectric structure with five arrays, which was successfully moulded using the separated mould process.

The researchers concluded that the PIM technology developed could be successfully replicated for the high-volume fabrication of high-precision and defect-free micro-sized piezoelectric structures with high aspect ratio.

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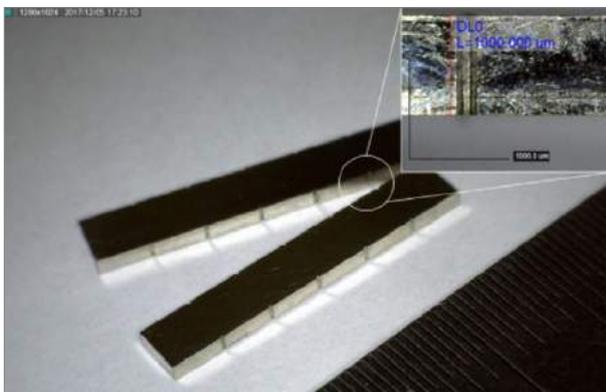


Fig. 1 The fabricated separated mould system used to produce micro-sized piezoelectric structures (From the paper 'Fabrication of micro-sized piezoelectric structure using powder injection molding with separated mold system', by JM Park, et al, *Ceramics International* Vol. 44, 2018, pp 12,709-12,716)

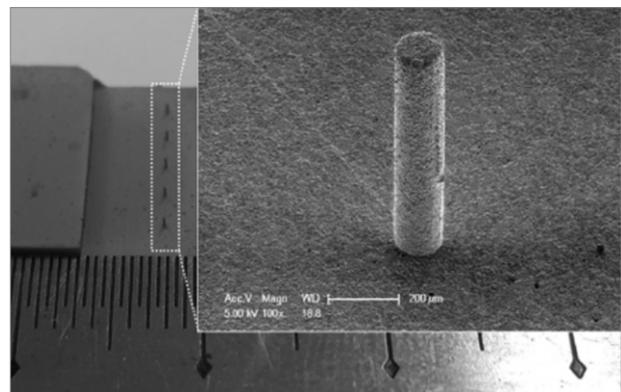


Fig. 2 Sintered part of micro-sized piezoelectric structure (From the paper 'Fabrication of micro-sized piezoelectric structure using powder injection molding with separated mold system', by J M Park, et al, *Ceramics International*, Vol. 44, 2018, pp 12,709-12,716)

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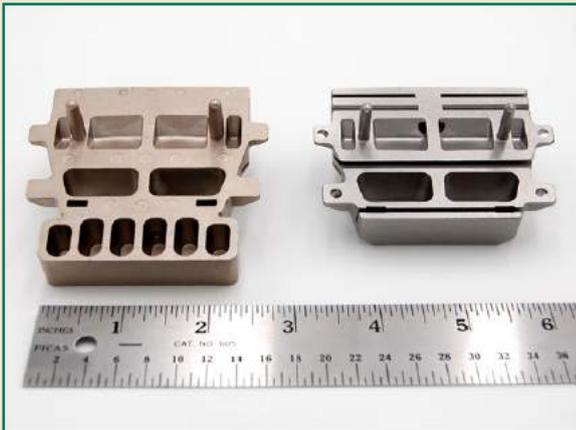
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# Threat or opportunity?

## The MIM industry as a partner, a target and a market for metal AM

In September, HP announced its entry into the world of metal Additive Manufacturing with the launch of a new binder-based AM system, the HP Metal Jet. The fact that HP's launch partners, Parmatech and GKN Powder Metallurgy, are well-known MIM producers serves to highlight just how close the worlds of AM and MIM have become; a fact evidenced by multiple launches and developments over the past few years. In this report, *PIM International's* Nick Williams reviews the attraction of AM for MIM producers, and the equally strong attraction of MIM for AM machine builders.

One of the most widely discussed barriers to the faster growth of the Metal Injection Moulding industry relates to the complex tooling that is required in a MIM process chain. The cost of this tooling, which can run into the tens of thousands of dollars, is one of the main reasons MIM production volumes still typically start at around 50,000 parts per year. Tooling also poses other challenges; complex MIM tooling is never quick to make and may require a number of modifications following first use to optimise part quality and production speed. This can add delays of many weeks to the timescale of a part entering full-scale production.

This barrier has long presented the promise of a lucrative business opportunity for anyone with the capability to produce small, complex, MIM-like components in volumes of up to 50,000 parts. Whilst there are some successful MIM companies who specialise in lower volume parts production, metal Additive Manufacturing has in recent years become an increasingly attractive proposition for MIM producers seeking to take advantage of this opportunity.

Of the MIM producers who adopted metal AM technology at a relatively early date, the choice of technologies and suppliers just five years ago was somewhat limited compared to today. Laser Beam Powder Bed Fusion (LB-PBF) systems from a range of vendors offered the ability to process

complex geometries from a number of materials, but the purchase price of these systems was extremely high, they were often unpredictable and complex to operate, and the metallurgy of the finished parts was very different to the isotropic grain structures found in Metal Injection Moulding.



*Fig. 1 Personalised automotive key fob components, such as these demonstrated by Volkswagen, have been produced on HP's Metal Jet system (Courtesy HP)*



Fig. 2 The new Metal Jet system (Courtesy HP)



Fig. 3 HP Metal Jet systems installed at GKN Powder Metallurgy (Courtesy HP)



Fig. 4 Parts manufactured using HP's Metal Jet system on display at Formnext

Early Binder Jet systems, such as those offered by ExOne, provided an alternative and capable solution, but the reality was that neither technology was at the time optimised for series production, but rather for prototyping and tooling. Both types of system were nevertheless adopted by a number of MIM companies in Europe, Asia and the US.

In 2014, *PIM International* reported a move into Additive Manufacturing by ARC Group Worldwide, Inc., whose ARCMIM operation includes FloMet, based in the US, and Advanced Forming Technology (AFT), which has operations in both the US and Hungary. Expanding on its ARCMIM operations, the company made the move into the world of Additive Manufacturing with the creation of its 3DMT business. Commenting at the time, Ashley Nichols, General Manager of 3DMT and a well-known MIM industry figure, stated that ARC had expanded into AM for two reasons: "First, current MIM customers all want a full-service provider that can do rapid prototyping and short run production as well as MIM for mass production. Adding 3D printing capability provides the customer with a solution from the very first plastic prototypes used in concepts to functional metal parts for initial fit and function testing, as well as low-volume prototype lots to validate the product before making investments into mass production tooling."

Secondly, ARC also targeted a wider opportunity beyond MIM prototyping; the series production of 'designed for AM' parts. "3D printing is a great strategic complement to our MIM business and allows us to expand into new products and markets by providing a solution to our customers that wasn't available in the past," stated Nichols in 2014. ARC's ambitious move to create 3DMT has proven to be well-judged. Today, the business operates more than fifteen metal LB-PBF systems, including EOS's large flagship four-laser M 400 machine. ARC

recently stated that it is now planning the sale of 3DMT.

Singapore-based MIM producer Advanced Materials Technologies Pte Ltd (AMT) also established a new '3D metal printing' centre, stating in 2015 that it was offering metal Additive Manufacturing services "to complement its existing range of mass-manufacturing processes." In addition to prototyping parts, AMT stated that it would also leverage Additive Manufacturing technology to meet the demand for small-volume batch production.

There are, of course, many other MIM producers around the world which have invested in AM technology, but the above examples effectively illustrate the motivations behind these investments.



Fig. 5 A prototype gear shift part made using the Metal Jet system (Courtesy HP)

## HP turns to MIM producers to support its move into metal AM

The world of metal Additive Manufacturing has evolved so dramatically in the last two years that today a host of new opportunities are available to MIM producers. Two of the MIM industry's most well-known companies, Parmatech, Petaluma, California, USA, and UK-headquartered GKN Powder Metallurgy, made the headlines in September when they were announced as the launch partners for HP Inc's new metal Additive Manufacturing platform, the HP Metal Jet (Fig. 2), at the International Manufacturing Technology Show (IMTS) in Chicago, Illinois, USA.

HP's new system – one of several 'next-generation' Binder Jet systems to launch on the market specifically aimed at volume production – claims to provide mechanically functional parts at significantly higher levels of productivity compared to existing Binder Jet or LB-PBF technologies. Utilising a voxel-level Binder Jetting technology, the first material available for use with the HP Metal Jet is stainless steel, providing finished parts with properties that, it is reported, meet or exceed ASTM and



Fig. 6 An impeller (cutaway view) manufactured using HP Metal Jet technology for Wilo (Courtesy HP)

MPIF Standards for tensile strength, yield strength and elongation. The new system costs around \$400,000, with shipping commencing in 2020. Of note – and differentiating the system from its competitors – is the fact that the HP Metal Jet system uses a very small volume of binder, eliminating the need for a debinding step and, in theory, lifting the restrictions on wall thicknesses that govern the design of MIM parts.

At the Metal Jet's high-profile launch, Dion Weisler, CEO and President of HP Inc, commented, "We are in the midst of a digital

industrial revolution that is transforming the \$12 trillion manufacturing industry. HP has helped lead this transformation by pioneering the 3D mass production of plastic parts and we are now doubling down with HP Metal Jet, a breakthrough metals 3D printing technology. The implications are huge – the auto, industrial and medical sectors alone produce billions of metal parts each year. HP's new Metal Jet 3D printing platform unlocks the speed, quality and economics to enable our customers to completely rethink

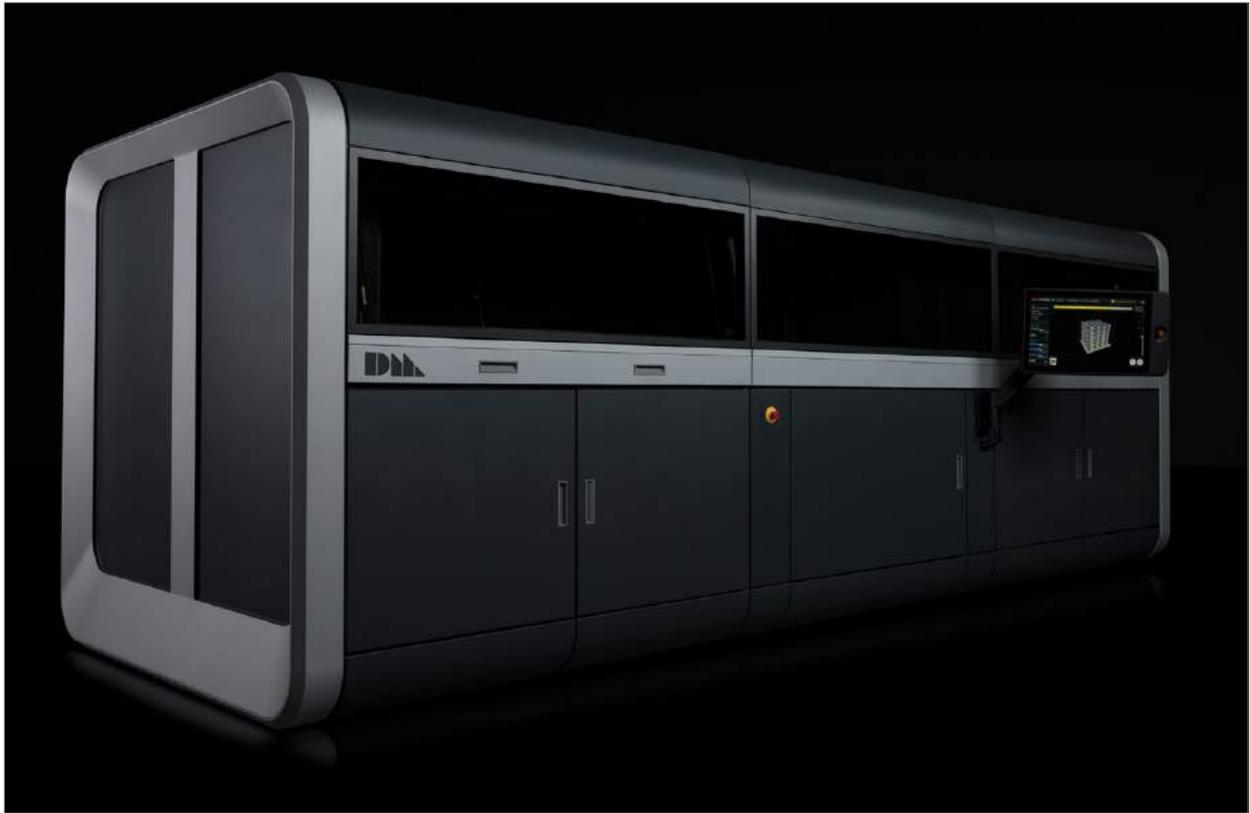


Fig. 7 Desktop Metal's Production System is scheduled to ship in 2019 (Courtesy Desktop Metal)

the way they design, manufacture and deliver new solutions in the digital age."

HP's partnership with Parmatech, the company at which MIM was invented and commercialised in the late 1970s and early 1980s, and GKN Powder Metallurgy, the world's largest producer of sintered metal parts and owner of a large MIM plant in Bad Langensalza, Germany, is vital for the company. As a business, HP has unrivalled experience in inkjet technology and plastic 3D printing. What it lacks – along with almost all of its rival developers of binder-based metal AM systems – is the deep understanding of the sintering and related metallurgical processing of high volumes of complex components that MIM companies possess.

HP's decision to partner with MIM producers not only brings on board experienced teams of specialists who can help refine the various systems and processes to deliver the

promised results of faster speeds, high reproducibility and lower costs, but also delivers a ready-made pool of potential customers who are already comfortable with MIM processing. Crucially, these MIM producers already have the necessary sintering capacity installed.

The appointment of Paul Hauck, veteran of the MIM industry and former president of the MPIF's Metal Injection Moulding Association, as Product Manager for E2E Hardware Solutions at HP Metal Jet serves to reinforce just how intertwined these two technologies are becoming.

GKN Powder Metallurgy has stated that it will use the HP Metal Jet system in its factories to produce functional metal parts for auto and industrial customers including Volkswagen Group and Wilo SE, a global leader for pumps and pump system solutions headquartered in Dortmund,

Germany. Peter Oberparleiter, CEO of GKN Powder Metallurgy, stated at the time of HP's announcement, "We're at the tipping point of an exciting new era from which there will be no return: the future of mass production with 3D printing. HP's new Metal Jet technology enables us to expand our business by taking on new opportunities that were previously cost-prohibitive."

Volkswagen is reported to be integrating the HP Metal Jet into its long-term design and production roadmap, and the collaboration has resulted in the ability to move quickly to assess the manufacturing of mass-customisable parts as well as higher-performance functional parts. As new platforms, such as electric vehicles, enter mass production, the HP Metal Jet is expected to be used in additional applications.

Wilo will also look to HP's Metal Jet technology to produce hydraulic parts such as impellers, diffusers

and pump housings with widely variable dimensions that must withstand intense suction, pressure and temperature fluctuations. A demonstration part can be seen in Fig. 6.

Parmatech will use HP's Metal Jet system to expand the mass production of medical parts for its customers, including OKAY Industries and Primo Medical Group. Parmatech believes Binder Jet technology will play a key role in developing innovative solutions for the unique challenges of its customers. Rob Hall, President of Parmatech, stated, "HP Metal Jet represents the first truly viable 3D technology for the industrial-scale production of metal parts. We are excited to deploy HP Metal Jet in our factories and begin manufacturing complex parts, such as surgical scissors and endoscopic surgical jaws, and new applications and geometries not possible with conventional metal fabrication technologies."

## Other Binder Jet machine producers targeting series production

### Desktop Metal

HP is not the only company moving into the market for the series production of metal components by Binder Jetting. In 2017, Desktop Metal, based in Burlington, Massachusetts, USA, announced two new metal Additive Manufacturing systems which together cover "the full product lifecycle from prototyping to mass production." Whilst the company's Studio System, now commercially available, uses what are essentially rods of MIM feedstock in an extrusion process to form a part, the company's Production System (Fig. 7) uses a Binder Jetting process to achieve higher volume production.

This system, reported to be in final testing with beta customers, is scheduled to begin shipping in 2019 and will compete directly with HP's Metal Jet system in the marketplace. Here too the MIM industry connec-



Fig. 8 ExOne's forthcoming X1 25PRO metal AM system is targeted at series production (Courtesy ExOne)

tion is never far away, with MIM veteran Animesh Bose holding the position of Vice President of Research and Development at Desktop Metal.

### ExOne

At the recent Formnext exhibition in Frankfurt – now widely recognised as the world's leading event for industrial Additive Manufacturing – The ExOne Company, North Huntingdon, Pennsylvania, USA, introduced its forthcoming X1 25PRO™ metal AM system (Fig. 8), targeted at series production. ExOne was founded in 2005 as a spin-off of Extrude Hone Corporation, which was in 1996 the exclusive licensee of the process developed at Massachusetts Institute of Technology (MIT) for the AM of metal parts and tooling. The company's current systems are well established in the international marketplace thanks to its deep heritage in Binder Jetting, and

numerous MIM suppliers, research institutes and part producers are cited as ExOne customers, including Sandvik AB, Carpenter Technology Corporation, Global Tungsten & Powders Corp and MiMtechnik GmbH.

ExOne's new system is reported to be able to combine the processing capability of its INNOVENT+™ machine with production volume capability that "addresses the needs of MIM, Powder Metallurgy, and manufacturing customers seeking a larger platform solution for producing parts in a production environment." It also allows customers of the INNOVENT+ platform to scale up to a mid-size production platform using the same standard powders they are currently using. Systems are expected to be delivered starting late 2019.

As the company's technology has been available for a relatively long period, a much wider choice



Fig. 9 A production line of Digital Metal's DM P2500 metal Binder Jetting systems (Courtesy Digital Metal)

of materials is available from ExOne, including 316L, 304L and 17-4PH stainless steels, Inconel 718 and 625, M2 and H11 tool steels, cobalt chrome, copper, and tungsten carbide cobalt.

### Digital Metal

Digital Metal, part of Sweden's Höganäs Group, has been using its proprietary Binder Jet technology in-house to produce precision small-scale components for customers since 2013, and had manufactured more than 200,000 parts before it made its system, the DM P2500, commercially available in September 2017. In October this year the company presented what it describes as a fully automated 'no-hand' production concept for the series production of components using metal Binder Jetting technology (Fig. 9). In this concept, the majority of the process steps involved in part production will be handled by a robot, eliminating most of the manual

work involved and thus increasing productivity.

The robot feeds the printer with build boxes, which are then moved for post-treatment in a CNC-operated depowdering system combined with a pick-and-place robot. There, the remaining metal powder is removed and recycled, and the parts placed on sintering trays before being moved by the main robot to the sintering furnace for combined debinding and sintering, either in batches or for continuous production.

Ralf Carlström, General Manager at Digital Metal, stated, "Most AM technologies show a very low level of automation. Our aim is to change that. With the new no-hand production line, our customers can further improve their productivity and lower the production costs. Almost all manually intensive work can be eliminated and, in addition, the powders removed in the cleaning machine can be recirculated in the process, thus minimising waste. As we see it,

the Digital Metal technology is now applicable for the serial production of high-volume components."

Digital Metal's DM P2500 system is currently in use for the production of parts in series of up to 40,000 components. In 2018, the company signed a number of delivery agreements with major European automotive and aerospace companies. "We believe there is a huge potential for our unique technology," added Carlström. "Not only is it very fast and cost-effective, it is also able to create complicated and highly detailed designs with wide material choice."

In an interview in the Spring 2018 issue of *Metal AM* magazine, Carlström stated that he sees Binder Jet Additive Manufacturing as a complementary technology, rather than a threat, to MIM. "There are many similarities with MIM and Digital Metal technology," he explained. "Sintering, used by both processes, provides the strength of the components. It results in

similar mechanical properties, densities and microstructures. The established standards used by the MIM industry are also therefore applicable for our technology; the depth of knowledge and infrastructure, in terms of sintering furnaces for example, already exists in MIM. Therefore, we see our technology as a logical complement to MIM for the production of prototypes or small series."

An area in which Binder Jet AM might pose a threat to Metal Injection Moulding, Carlström noted, is in the production of parts with complex internal features, for example cooling channels or ducts for the transmission of fuel or fluid. Using MIM, parts with hollow internal structures must be moulded in two parts and subsequently welded together. By enabling the production of such components as a single part, Binder Jetting has major potential for the series production of components for aerospace, automotive and other industries where part consolidation, and the resulting weight, material and time savings, are key.

### MIM feedstock-based metal AM as a low-cost route for MIM producers

Whilst Binder Jetting is the most production-ready of the MIM-like AM technologies, solutions that use MIM feedstock variants rather than a separate powder and binder are proliferating. These processes fall into the category of extrusion processes and Fused Filament Fabrication (FFF). A selection of such systems that have the potential to be used for low-volume production are highlighted below.

#### Desktop Metal's Studio+ System

In September 2018, Desktop Metal announced its extrusion-based Studio System+ and Studio Fleet offering. The Studio System+ includes the office-suitable features of the original Studio System, but is said to have added functionality for



Fig. 10 An award winning nozzle with internal channels manufactured by Digital Metal, diameter approximately 15 mm [Courtesy Digital Metal]



Fig. 11 A windshield washer nozzle for supercar manufacturer Koenigsegg containing a number of internal performance-enhancing functions [Courtesy Digital Metal]

the production of small metal parts at higher resolutions. The Studio Fleet is a custom-configurable solution which, it states, is designed to address challenges in low- to mid-volume part production (Fig. 12).

The original Studio System was branded as the world's first office-friendly metal AM system for rapid prototyping, intended to make metal AM more accessible, thereby enabling design and engineering teams to produce metal parts faster and without the need for special facilities, dedicated operators or expensive tooling. The three-part solution comprises the AM machine, a debinder and a furnace. Process

automation is available by integration with Desktop Metal's cloud-based software.

The Studio System+ is said to incorporate new print capabilities as well as hardware updates designed for increased throughput. A new swappable high-resolution printhead with supporting software profiles is said to allow the production of parts at higher resolutions, with finer features and improved surface finish. According to Desktop Metal, this "opens up opportunities for new geometries and applications, with the ability to additively manufacture parts similar to those produced by MIM."



Fig. 12 An example of Desktop Metal's Studio Fleet showing five AM systems, two debinders and one furnace [Courtesy Desktop Metal]

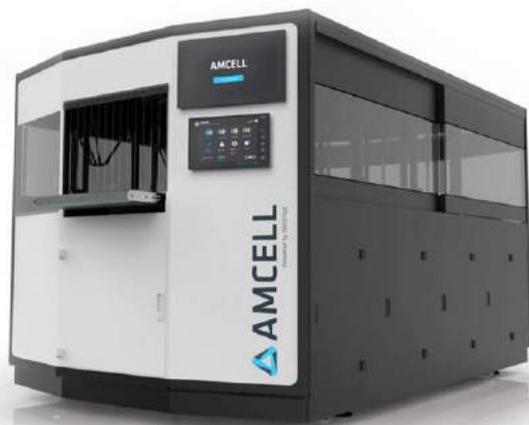


Fig. 13 Trititive's AMCell Additive Manufacturing machine said to be capable of producing up to 10,000 green parts per month using BASF's Ultrafuse 316LX filament

### The Metal X from Markforged

Markforged, Watertown, Massachusetts, USA, also manufactures parts using a feedstock extrusion process. To date, over one-hundred Metal X systems have been shipped to customers globally, and the company expects to more than double that number by the end of 2018. As with Desktop Metal's Studio system, the Metal X is offered as a complete solution, with a dedicated build unit, debinding station and a choice of two sintering furnaces. The company states that the system can "enable large-

scale manufacturers to produce functional prototypes, tools and fixtures, injection moulds and end-use parts in metal."

### AIM3D: Extrusion of MIM feedstock pellets

AIM3D, Rostock, Germany, has developed a compact extruder that processes MIM feedstock pellets directly and can achieve build rates of up to 160 cm<sup>3</sup> per hour depending on the nozzle. Customers can choose the nozzle's diameter, down to 250 µm, and can choose between water, solvent-based, or catalytic material systems.

### BASF Ultrafuse 316LX fused filament material

BASF SE's Catamold feedstock is synonymous with the high-volume production of components by MIM, and BASF has now adapted this technology for metal Additive Manufacturing via Fused Filament Fabrication (FFF) with the development of its Ultrafuse 316LX filament.

The technology offers MIM customers a low-investment route into metal AM, whether for prototyping or the development of entirely new applications. Ultrafuse 316LX can be used with almost any FFF AM system and, once a part is built, no additional post-processing steps are required prior to its debinding and sintering.

### Trititive system for parts production using Ultrafuse feedstock

Trititive, an Additive Manufacturing machine maker based in Gijón, Spain, recently launched AMCell (Fig. 13), a hybrid and automated Additive Manufacturing machine said to be capable of producing up to 10,000 green parts per month using BASF's Ultrafuse 316LX filament.

According to CEO Mariel Diaz, "The green parts printed with AMCell using BASF's metal filament solution meet the geometric and surface quality requirements for mass-manufacturing of final parts. The controlled build chamber environment in the AMCell and its optimised extrusion process achieve part porosities similar to those that are typically obtained from Metal Injection Moulding technology."

AMCell claims that its capability for the automated manufacturing of large part batches, and the use of Ultrafuse 316LX, greatly eases the material handling process by eliminating potential hazards inherent to other metal powder AM processes. The automatic load and consumption control of Ultrafuse 316LX filament spools allows the system to operate largely unsupervised during the whole production process, and reduces human labour and intervention to a minimum.



Fig. 15 GKN Powder Metallurgy and HP promote binder-based Additive Manufacturing at Formnext 2018. The image highlights the scale of the marketing push behind these news technologies (Courtesy Formnext / Mesago Messe Frankfurt GmbH)

### Can these technologies really match MIM?

Whilst there is undoubtedly a lot of excitement – some might call it hype - around the potential of these technologies, from a MIM producer's perspective there is a diversity of opinion when it comes to how they will develop and become either an opportunity or a threat. As matters stand today, MIM clearly has a number of unique advantages that set it apart from MIM-like AM technologies, most notably its maturity as a technology, its excellent as-sintered surface finish, superior mechanical properties, efficient high-volume production capabilities and the wide choice of materials available.

MIM has always struggled to compete in small series production, and it is here that these AM technologies have the potential to

make in-roads. Certainly, some of the new systems coming to market are yet to be proven in terms of consistent part quality over larger production runs. However, given the speed at which the world of metal AM is evolving and improving - thanks in large part to the huge financial investments being made in R&D - rapid progress in productivity, surface resolution and quality are an inevitability. When one adds to this the potential for previously unimaginable part complexity, with internal channels and design features that simply could not be moulded, the opportunities for Binder Jetting become even more compelling.

Whilst it is by no means clear just what percentage of MIM producers have already started adding AM capabilities in-house, either for small series production, prototyping or simply for the manufacture

of fixtures and tooling, there is sufficient evidence to suggest that momentum is building. The range of volumes at which AM is more economical than traditional processes is undoubtedly increasing, and the opportunity to diversify beyond conventional MIM markets is an added draw.

What is clear is that manufacturers of AM machines that use either a binder or a thermoplastic feedstock see the MIM industry as a world of rich opportunities. On the one hand, small series MIM applications are regarded as low hanging fruit ready for picking, whilst on the other hand the MIM industry itself - as HP has demonstrated - is also recognised as both a potential development partner and customer. It will be very interesting to see how this dynamic changes in the coming years.

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# WORLDPM2018 Congress: Global MIM markets show healthy growth

The WORLDPM2018 Congress & Exhibition, Beijing, China, highlighted not only the rapid industrial growth that has been achieved in the country over the past two decades, but also the many advances made in PM materials and production technology. This applies equally to Metal Injection Moulding, which has been enjoying high growth in China as well as in other regions around the world. In this report, Bernard Williams summarises the global status of MIM as well as production and technology trends based on key presentations given during WORLDPM2018's Plenary and Special Interest Sessions.



## The global status of Metal Injection Moulding

Matthew Bulger, former president of the Metal Injection Molding Association (MIMA) and currently Administrative Director of the Association for Metal Additive Manufacturing (AMAM) in Princeton, New Jersey, USA, gave an overview of the world status of Metal Injection Moulding in the opening Plenary Session of the WORLDPM2018 Congress [1].

Bulger put the development of MIM into a historical context by stating that, when the technology was first used for the production of structural parts in the 1980s, most start-up MIM operations in North America were small, entrepreneurial and used binder and processing technologies under licence. This MIM technology, using paraffin wax/polyethylene binders, soon spread to Singapore, Japan, Taiwan and Europe, but little equipment - such as moulding machines and debinding/sintering furnaces - was available specifically

for MIM. Similarly, powder sources for MIM were hard to find, said Bulger, and the early low-alloy steel feedstocks were based primarily on Fe-2Ni using carbonyl iron powder. Early MIM part adoption was led by dental (orthodontic) and firearms producers.

In the 1990s, powder producer BASF SE, Germany, started its Catamold MIM feedstock programme using carbonyl iron powder. At the same time Epson/Atmix (Japan), Carpenter (USA) and Sandvik Osprey (UK) began producing grades of atomised stainless steel powders,



Fig. 1 More than a thousand delegates from thirty two countries attended the WORLDPM2018 Congress, organised by the Chinese Society for Metals (CSM) and China Powder Metallurgy Alliance (CPMA) (Courtesy WORLDPM2018)

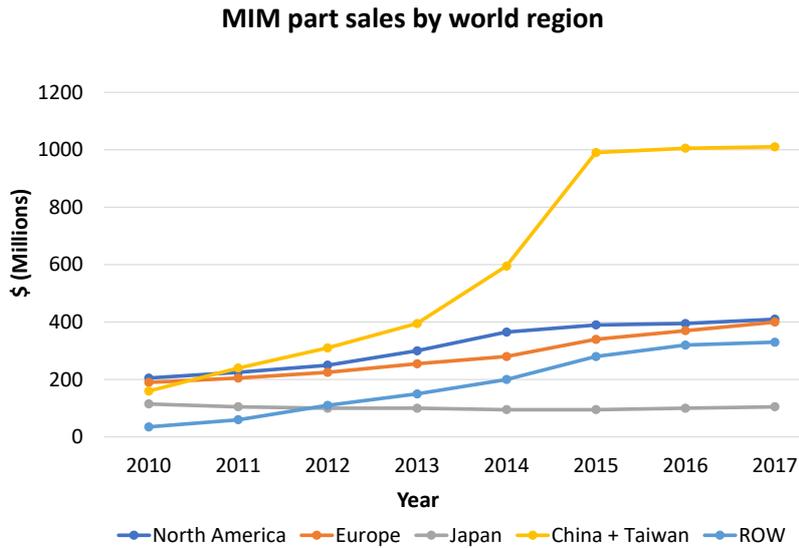


Fig. 2 Trends in global MIM markets show the impact of high growth in China/Taiwan since 2013 and steady growth in other regions [1]

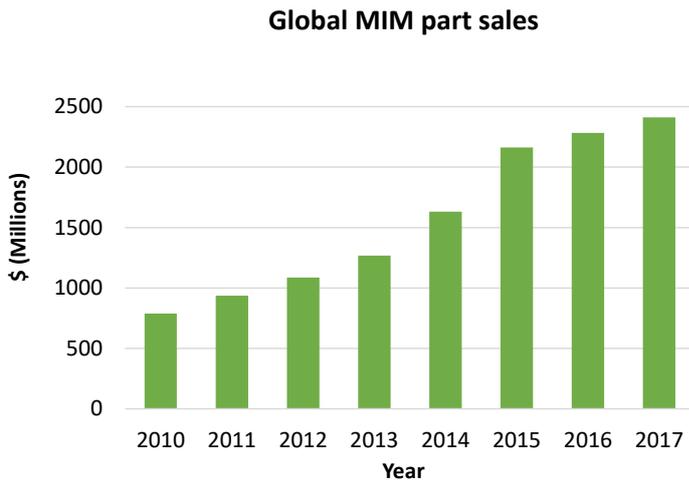


Fig. 3 Global MIM sales were estimated to be around \$2.4 billion in 2017, with average annual growth rates of 18% since 2010 [1]

Worldwide usage of MIM feedstock and powders		
Material	Feedstock (tons)	Powder (tons)
Stainless steel	10,000	9,000
Fe-based	6,700	6,030
Other	2,200	1,980
Tungsten	600	570
Titanium	275	220
Copper	430	390
<b>Total</b>	<b>20,205</b>	<b>18,190</b>

Table 1 Estimate of worldwide MIM powder and feedstock sales [1]

especially 17-4 PH, suitable for MIM applications. This, stated Bulger, encouraged larger manufacturers such as Precision Castparts, GKN, Swatch (ETA) and Epson to invest in volume MIM component production. However, there was still little standardisation of production equipment.

Bulger stated that MIM continued to gain interest in the new millennium, having become an established high-volume production technology. MIM standards had been published on a limited number of materials properties and these helped to define end-user expectations. Advances in powder production technology ensured adequate supplies of ultrafine powders at lower costs and new high-temperature alloy powders made possible the introduction of high-volume production of MIM turbocharger vanes for the European automotive market. Early applications for MIM in the high-volume electronics sector included the hinges for Motorola's flip phones.

By 2010, MIM production had expanded further around the world, with operations in Korea, India and China, and there was steady growth in MIM applications in Europe and North America. Moulding machines and debinding equipment were now being designed specifically for MIM, and automation was used increasingly to assist in high volume MIM part production.

**MIM - a leading advanced manufacturing technology**

Bulger stated that MIM is now recognised as one of the top ten advanced manufacturing technologies, ranking only second to Additive Manufacturing. MIM has achieved huge success over the past seven years, particularly in electronic applications in Asia since 2013, with growth averaging 18% per year (Fig. 2). The last three years have seen slower growth rates closer to 6% per year. Bulger estimated the global market for MIM to be in the region of \$2.4 billion; Fig. 3 shows growth trends for MIM in global markets since

2010. Fig. 4 gives a breakdown of the main application areas for MIM in North America. Bulger reported that, whilst consumer electronics applications such as mobile devices and computers dominate MIM applications in China/Taiwan, firearms and medical applications are prevalent in North America and automotive MIM applications in Europe.

**Powder and feedstock**

The rapid rise in the MIM sector since 2010, particularly in Asia, has contributed to a significant increase in MIM feedstock and powder sales. Bulger estimated worldwide powder sales at 18,190 tons and feedstock sales at 20,205 tons (Table 1). Stainless steel grades make up around 50% of sales, followed by Fe-based grades, with carbonyl iron powder remaining the main source for low-alloy steels, and atomised (gas and water) powders dominating stainless steel powder grades. Bulger stated that there has also been a shift to the outsourcing of MIM feedstock production. This, he said, was below 10% in the 1990s but it is now estimated that over 70% of

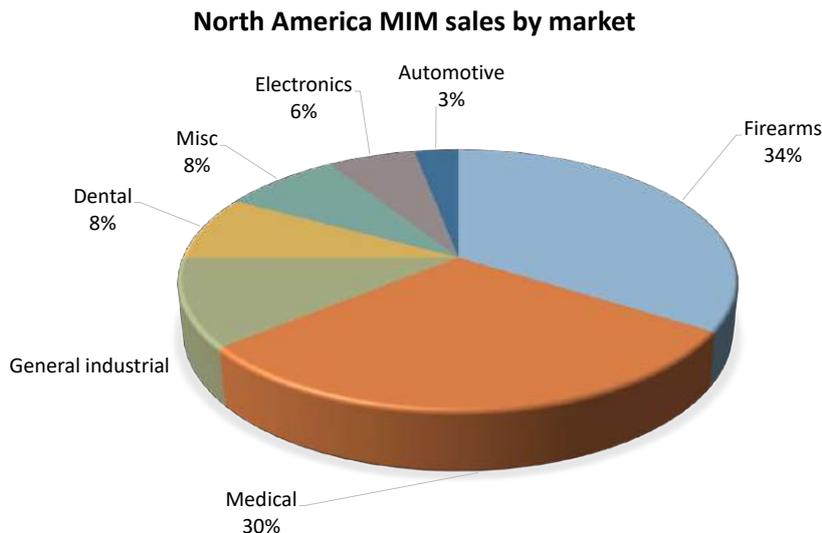


Fig. 4 Breakdown of North America MIM sales by market [Data MPIF] [1]

**Outlook**

Bulger cited a number of opportunities and challenges for future growth in the MIM industry. He observed the need to improve dimensional control in MIM manufacturing in order to eliminate expensive secondary operations; variations in part dimensions generally come from all steps of

The strong collaboration across the MIM supply chain needs to continue. However, Bulger stated that high powder costs and production issues, such as the greater shrinkage of larger parts in sintering, needed to be addressed in order for the MIM industry to economically produce larger MIM parts (>100 g). If these issues are not addressed, the likely outcome is that MIM will stay focused on smaller parts. The rapid rise of metal Additive Manufacturing, which uses MIM grade powders to produce complex metal parts, could benefit MIM producers with increased volumes of powders destined for AM, thus potentially lowering prices for fine metal powders overall.

*“The rapid rise in the MIM sector since 2010, particularly in Asia, has contributed to a significant increase in MIM feedstock and powder sales. Bulger estimated worldwide powder sales at 18,190 tonnes and feedstock sales at 20,205 tonnes”*

feedstock production is outsourced, with feedstock producers taking a bigger role in selecting powder sources and alloy development. BASF remains the dominant player across the globe with its catalytic debinding feedstock, but is facing increased competition from other feedstock producers as its patent protection is reduced.

the MIM process, and these are normally addressed by coining or machining, thereby adding considerable cost to the parts. Improved powders/feedstock will lead to more consistent moulded and sintered densities, and improving variations in sintering furnaces can also have a large beneficial impact.

**MIM in Europe**

Prof Dr Frank Petzoldt from the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM), Bremen, Germany, presented a report on the current situation for the MIM industry in Europe in a Special Interest Session at the congress [2]. Dr Petzoldt stated that MIM sales grew by a healthy 11% in terms of volume, and by 9% in sales value to over €400 million in 2017 (Fig. 5).

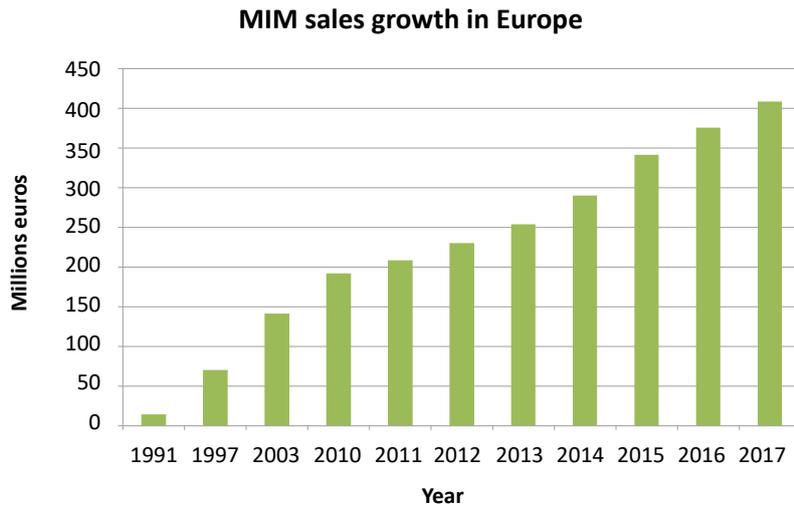


Fig. 5 European MIM sales grew by a healthy 9% by value in 2017 [2] (Source: EPMA market research)

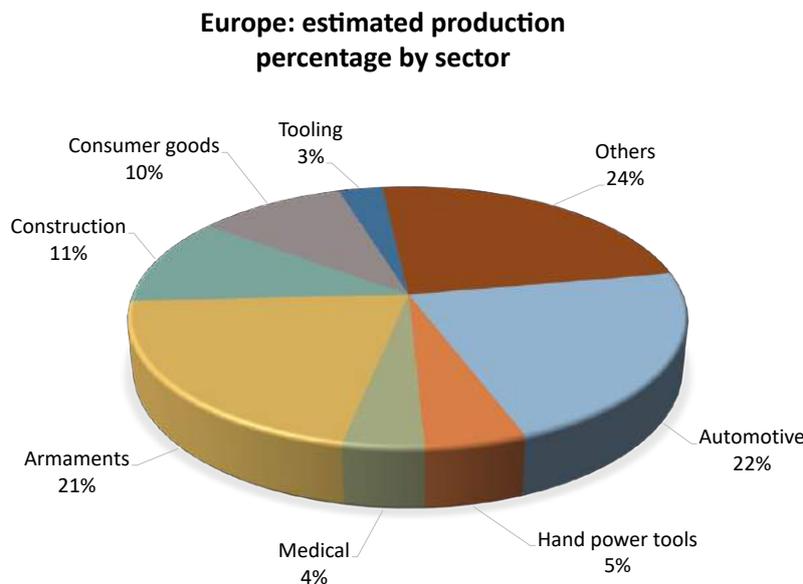


Fig. 6 European MIM sales grew by a healthy 9% by value in 2017 [2] (Data: EPMA Annual MIM Survey 2017)

Europe is said to make up around 28% of the global MIM market and, within Europe, Germany has the dominant market share at 29%, followed by Italy at 18% and France at 14%. As in other regions around the world, Dr Petzoldt stated that stainless steel MIM parts have the largest market share at around 50%. Fig. 6 shows the diversification of end-user markets for MIM components in Europe.

Dr Petzoldt stated that the European MIM industry is strongly

supported by a substantial number of research institutes, and that both the EuroMIM group at the European Powder Metallurgy Association and the German MIM Expertenkreis are active, not only in technology development and research but also in dissemination and promotion of MIM as an advanced manufacturing technology. Membership of these groups includes MIM part producers as well as powder and equipment suppliers.

Most European MIM companies use catalytic debinding systems to produce MIM parts, with around half the producers now using continuous debind/sintering furnaces, stated Dr Petzoldt. He added that around 80% of the companies use robotic devices for handling parts from moulds, and a similar percentage are expecting to increase their production capacity in the near future.

**A trend towards larger, heavier parts**

In terms of technology trends, Dr Petzoldt believes that European MIM part producers will be able to meet the challenges needed to produce larger, heavier parts. Powder and feedstock price has a significant influence on the competitiveness of larger MIM parts, as has distortion of such parts in sintering, he said. He gave two examples of successful larger MIM parts: one is a steel sensor housing weighing 67.3 g used in the automotive sector and developed by Schunk Sintermetalltechnik GmbH in Germany (Fig. 7), and a second part weighing 200 g developed by Mimecrisa in Spain for a professional power tool (Fig. 8).

**Two-material MIM**

Another trend in Europe is the injection moulding and co-sintering of two material components (2C-MIM), which not only eliminates the joining process step, but also opens up new perspectives for adding functional properties to MIM parts. The example given by Dr Petzoldt is a bi-material fuel injection valve sleeve demonstrator, developed by Robert Bosch GmbH, having high aspect ratio and thin walls (650 µm). The part combines the soft magnetic 430 material having high permeability with a non-magnetic 314 separation material.

**MIM functional materials**

The third trend cited by Dr Petzoldt is the development of functional MIM materials such as Ni-base superalloys for high temperature aero engine applications. The MIM

superalloy parts are suitable for operating conditions exceeding 700°C and offer excellent high cycle fatigue properties, high creep resistance and high corrosion resistance. Other functional MIM materials based on copper, composite materials, NdFeB, and LaFeSi are finding applications in medical technology, mobility, electronics and energy technology.

**The convergence of MIM and AM**

Dr Petzoldt pointed to the potential for MIM companies to use extrusion of MIM feedstock and also how MIM and metal Additive Manufacturing could complement each other in the future.

Extrusion uses less complex tools than those for injection moulding and, with suitable adaptation, MIM feedstock could be used in a continuous process with a high degree of automation to produce, for example, thin-walled tubular structures with functional cooling channels.

MIM and AM complement each other through the use of common feedstock material, he stated. MIM-like materials are used in the Fused Filament Fabrication and Binder Jetting AM processes to produce complex shapes in small series to high density (> 99%), and at a much higher production rate than, for example, Laser Beam Powder Bed Fusion. He sees a converging of the gap between AM for small series complex-shaped parts production and MIM parts in large series, as can be seen in Fig. 9.

**MIM in China**

The rapid growth of Metal Injection Moulding in China over the past decade was also underlined in a presentation in the Special Interest Session on PIM [3]. Putting this growth into a historical context, Prof Xuanhui Qu and Prof Gang Chen, from the Institute of Advanced Materials & Technology at the University of Science & Technology Beijing (USTB), stated that research into MIM technology at leading institutes such

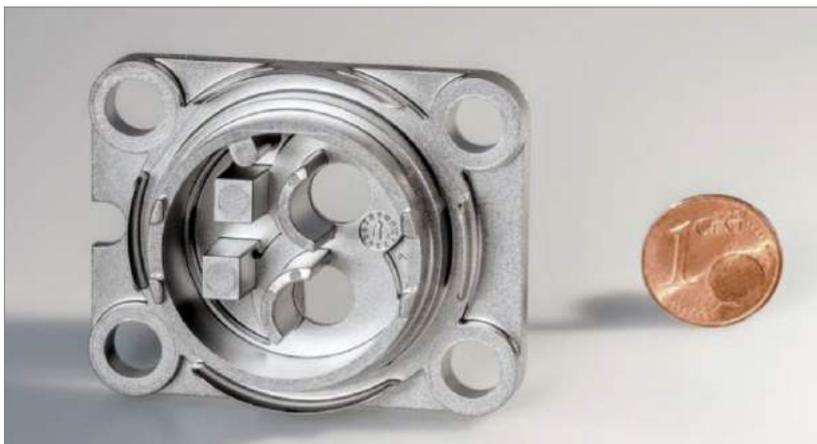


Fig. 7 MIM sensor housing weighing 67.3 g developed for the automotive sector by Schunk Sintermetalltechnik GmbH [2]



Fig. 8 Large MIM part weighing 200 g used in a professional power tool developed by Mimecrisa [2]

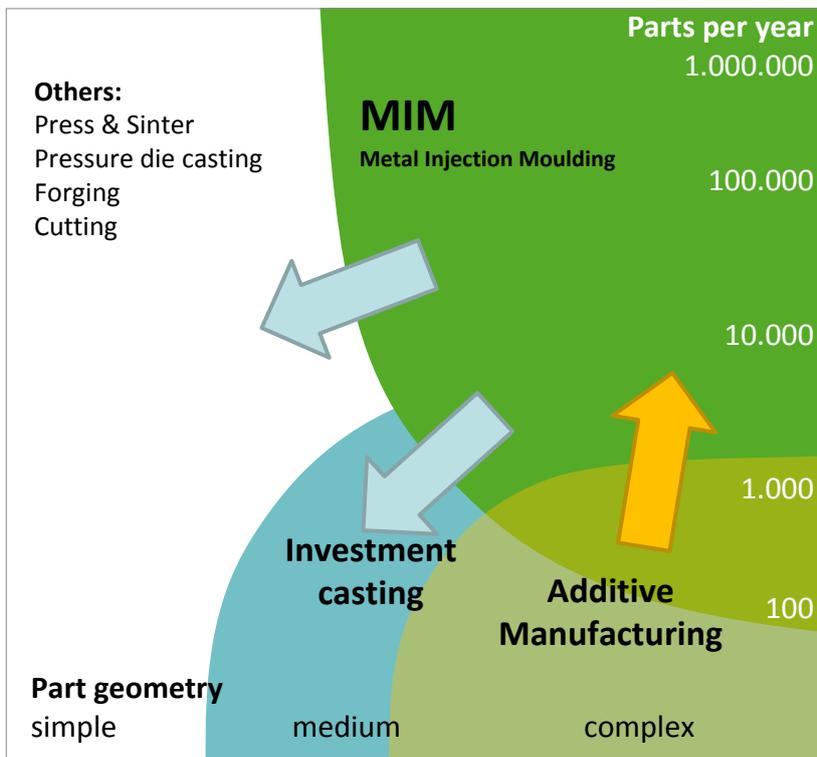


Fig. 9 MIM and metal AM could complement each other for the production of complex shapes [2]

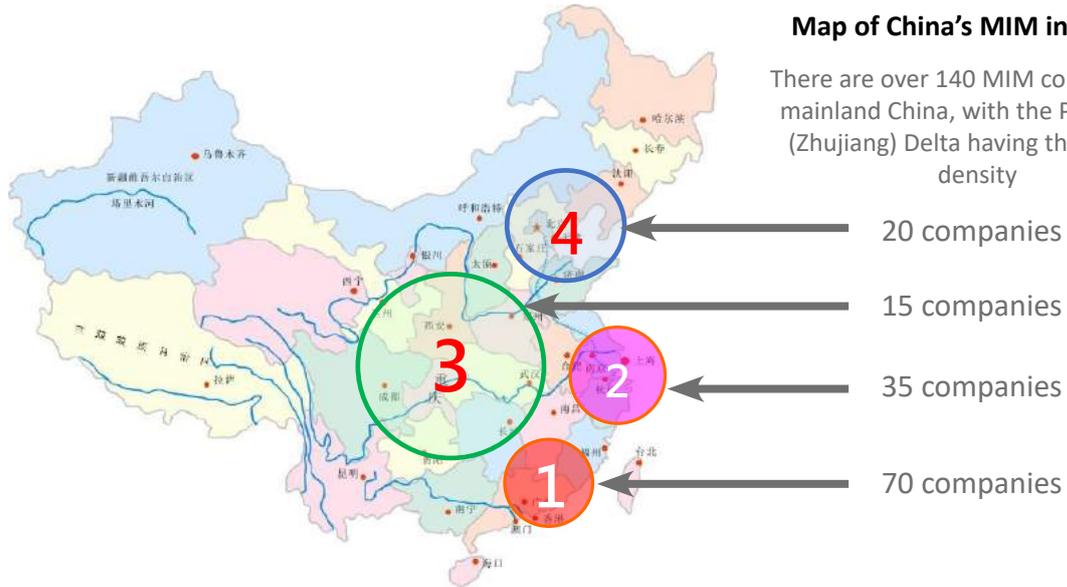


Fig. 10 Distribution of the main MIM manufacturing plants in China. Region 1 contains around 70 MIM companies with the most being found in Region 1, the Zhujiang Delta [3]

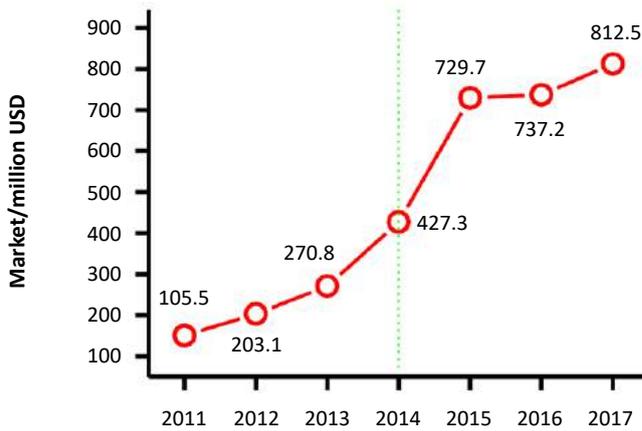


Fig. 11 MIM part sales have grown rapidly in China since 2010 [3]

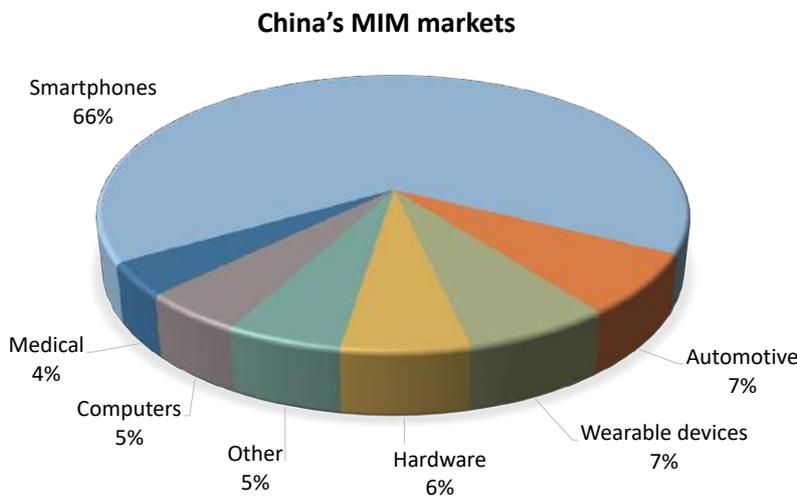


Fig. 12 Breakdown of MIM application areas in China [3]

as China Iron and Steel Research Institute (CISRI), Beijing, Central South University, Changsa, Hunan Province, and USTB started in the early 1990s. By the mid-1990s this research had laid the foundations for small batch MIM production at newly established start-up enterprises including Advanced Materials & Technology Ltd (AM&T) and Hunan Injection Moulding Ltd. Others soon followed and a number of MIM operations were established in the Zhujiang Delta industrial zone where many of the products for the world's leading electronics OEMs such as Huawei, Lenovo, Apple and Samsung are manufactured. This gave ready access to a fast growing market for 3C MIM parts, particularly for use in smartphones. The regional distribution of MIM companies in China is shown in Fig. 10.

**A dynamic market driven by consumer electronics**

Fig. 11 shows sales growth for the MIM industry in China since 2010. Sales of MIM parts were said to have reached \$812.5 million in 2017. In terms of the breakdown of materials used, stainless steels account for 70% of production, low-alloy steels 20%, tungsten-based materials 8% and other materials 2%. Fig. 12

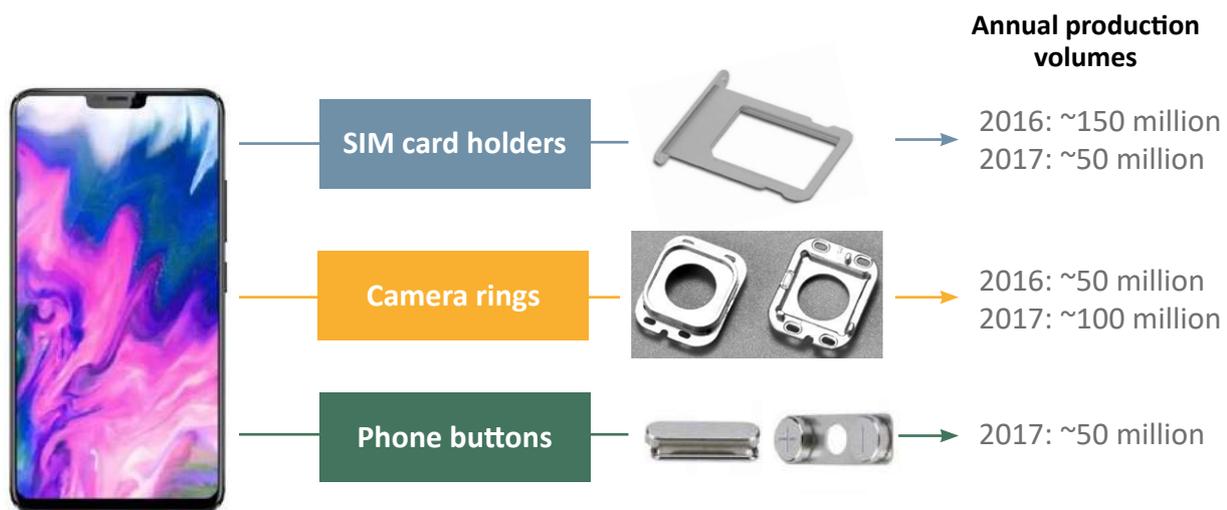


Fig. 13 Key MIM parts produced in China that are used in smartphones [3]

shows the breakdown of applications, with smartphones accounting for 66% of the MIM market in China. Prof Chen stated that the main MIM products in smartphones are SIM card holders, which he said saw production fall from 150 million pieces in 2016 to 50 million pieces in 2017, camera rings, of which 100 million were produced in 2017, and phone buttons, which reached 50 million pieces in 2017. (Fig. 13)

**Growth in Chinese MIM materials and production equipment**

Prof Chen underlined the important contributions made by Chinese powder manufacturers and equipment suppliers in helping to meet the increasing demand from the ever growing number of Chinese MIM producers.

Advanced Technology & Materials Ltd, which was established in Beijing as a start-up company using CISRI technology, has developed high-pressure water atomisation technology to produce spherical, ultra-fine stainless steel powders, and also vacuum gas and combined water/gas atomisation technology to produce low-oxygen, high-purity alloy powders.

AMC Powders Ltd, established in Beijing as recently as 2014, is using VIGA atomisation technology to

produce fine spherical powders in narrow particle size distributions, including titanium and titanium alloys, superalloys, nickel-chromium alloys, and stainless steels. Falcontech Ltd, based in Wuxi, also uses gas atomisation technology to produce superfine spherical titanium and Ti-alloy powders.

Prof Chen stated that Xiamen Honglu Tungsten Molybdenum Industry Ltd, located in Xiamen, is using a hydrogen reduction and milling process to produce tungsten based powders suitable for MIM parts such as tungsten-barium electrodes used for flashlights and lamp-pumped lasers, and complex-shaped MIM tungsten-copper components for thermal management applications. Prof Chen estimated that a total of 8,000 to 8,500 tonnes of metal powder was consumed by Chinese MIM producers in 2017, of which around 55% was sourced from domestic powder producers.

He further reported that around 80% of feedstock is produced in-house by MIM manufacturers. There are also a growing number of companies in China supplying MIM feedstock, however BASF remains by far the largest feedstock producer. There is a heavy reliance

on polymer-base binders for MIM feedstock in China, which Prof Chen stated provide the strength and precision required for MIM part production. R&D efforts are also underway in China to develop MIM feedstock with lower shrinkage rates to minimise distortion during debinding and sintering, hybrid debinding technologies to reduce debinding time in MIM part production, and feedstock which can be used for both MIM and MIM-like Additive Manufacturing processes.

A significant proportion of production equipment used by Chinese MIM companies, such as advanced injection moulding machines, specialised debinding furnaces and continuous debinding/sintering furnaces are now available from Chinese producers, added Prof Chen.

**Recent technology trends**

Pointing to some recent technology trends in China, Prof Chen showed an example of  $\mu$ MIM ZrO<sub>2</sub> gears, having different outer diameters that range from 200-1200  $\mu$ m, and central holes measuring 30-50  $\mu$ m. The  $\mu$ MIM gears were produced using a polymer-based binder system: BW:EVA:HDPE:SA = 5:45:20:10. Other  $\mu$ MIM parts being

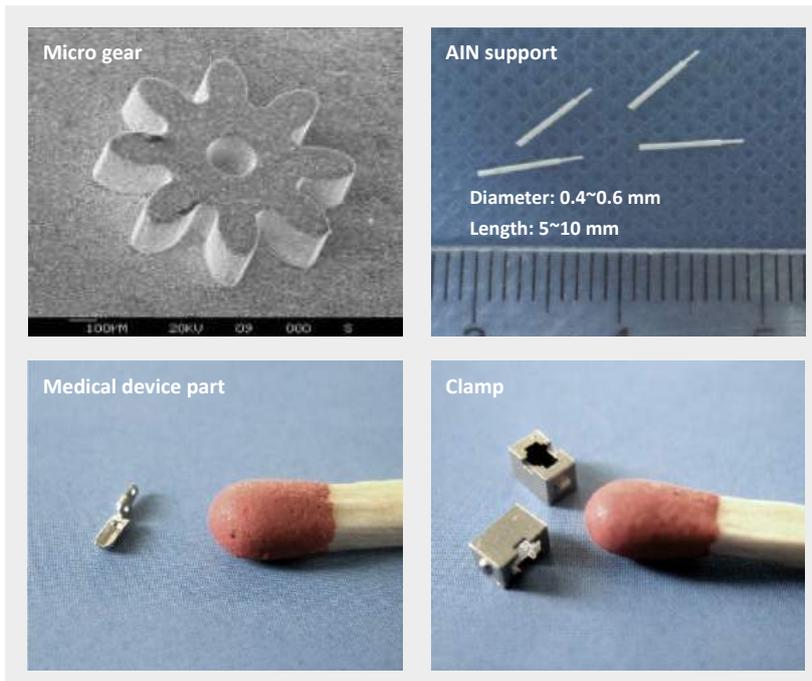


Fig. 14 Selection of  $\mu$ MIM parts developed in China [3]



Fig. 15 Examples of applications for AlN MIM parts [3]

developed include AlN supports having a diameter of 0.4-0.6 mm and length of 5-10 mm, a  $\mu$ MIM part used in a hearing aid and  $\mu$ MIM clamps (Fig. 14).

Prof Chen stated that AlN MIM and  $\mu$ MIM parts, used in microelectronics, aerospace and defence, show high thermal conductivity ( $234 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ),

excellent insulation, etc, and MIM can produce parts such as heat sinks, packaging shells, skeletons and micro supports to close dimensional tolerances (Fig. 15). He stated that MIM-grade AlN powders with various particle sizes are produced by a combination of carbothermal reduction and hydrochemistry. AlN-Si<sub>3</sub>N<sub>4</sub>

and AlN-SiC composite powders have also been produced with MIM applications in mind.

MIM parts made from high temperature IN718 grade nickel-base superalloy have been developed for turbochargers which have performed well during load testing, said Prof Chen. The thin wall MIM turbine wheels have a complicated shape with a groove and hole and must be produced to high dimensional tolerances for turbocharger applications (Fig. 16).

Soft magnetic materials, as used in micro yokes, yoke seats and armatures made by MIM at USTB using Fe-based alloys, have been found to have superior properties to conventionally produced soft magnetic materials, as can be seen in Table 2. The production of composite MIM parts is another area offering potential applications for MIM technology; one example given by Prof Chen is the infiltration of Al and Cu into a porous MIM SiC part to offer high heat conductivity and flexible thermal expansion. Ti, Ti alloy and TiNi alloys are also being investigated for a variety of applications including spectacle frame arms.

**Outlook**

Prof Chen concluded that, although MIM is now regarded as an established manufacturing process, MIM technology still has a promising and bright future in areas such as automotive, medical, energy (fuel cell plates), aerospace and even MIM and CIM cases for smartphones. However, the technology's prospects could be improved further by developing and using affordable powders. This would mean developing technology where expensive fine spherical powders could be replaced with cheaper fine irregular shaped powder, or even a coarser spherical powder.

**References**

[1] MIM World Status 2018, M Bulger, as presented at the WORLDPM2018 Congress, Beijing, China, September 16-20, 2018, and organised by the The Chinese Society for Metals (CSM) and

Material	Data	$B_{6000}$ (T)	$\mu_m$ (mH/m)	Hc (A/m)	Relative density (%)
Fe50Ni	US MPIF standard	1.50	59.0	12	-
	EU standard	1.50	37.7	15	95.6
	Ref.	1.50	74.1	10	96.8
	<b>USTB data</b>	<b>1.59</b>	<b>116</b>	<b>1.31</b>	<b>&gt; 99.5</b>
Fe79Ni4Mo	US MPIF standard	-	-	-	-
	EU standard	0.8	93.6	8	-
	Ref.	-	123	-	-
	<b>USTB data</b>	<b>0.873</b>	<b>250</b>	<b>0.53</b>	<b>&gt; 99.5</b>
Fe50Co	US MPIF standard	-	-	-	-
	EU standard	2.0	4.90	-	-
	Ref.	2.26	8.87	149	98.6
	<b>USTB data</b>	<b>2.40</b>	<b>11.7</b>	<b>62.3</b>	<b>&gt; 99.5</b>
Fe50Co2V	US MPIF standard	-	-	-	-
	EU standard	-	-	-	-
	Ref. 1.86	3.35	246	96.4	-
	<b>USTB data</b>	<b>2.30</b>	<b>9.62</b>	<b>87.9</b>	<b>&gt; 99.5</b>

Table 2 Comparison of properties of soft magnetic materials made by conventional processes and by MIM [3]

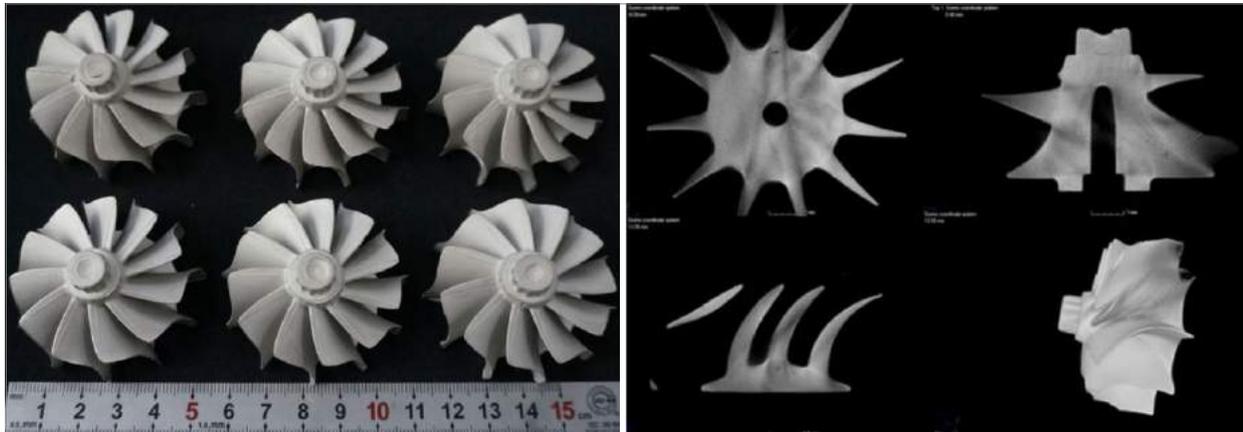


Fig. 16 Superalloy turbine wheels for turbochargers have been developed using MIM and achieved excellent performance in load testing [3]

China Powder Metallurgy Alliance (CPMA).

[2] Metal Injection Moulding in Europe - Technological trends and business situation, F Petzoldt, as presented at the WORLDPM2018 Congress, Beijing, China, September 16-20, 2018, and organised by the The Chinese Society for Metals (CSM) and China Powder Metallurgy Alliance (CPMA).

[3] Metal Injection Moulding in China - Recent developments and future perspectives, Xuanhui Qu and Gang Chen, as presented at the WORLDPM2018 Congress, Beijing, China, September 16-20, 2018, and organised by the The Chinese Society for Metals (CSM) and China Powder Metallurgy Alliance (CPMA).

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# Ceramic Injection Moulding and Ceramic Additive Manufacturing side by side: Opportunities and challenges

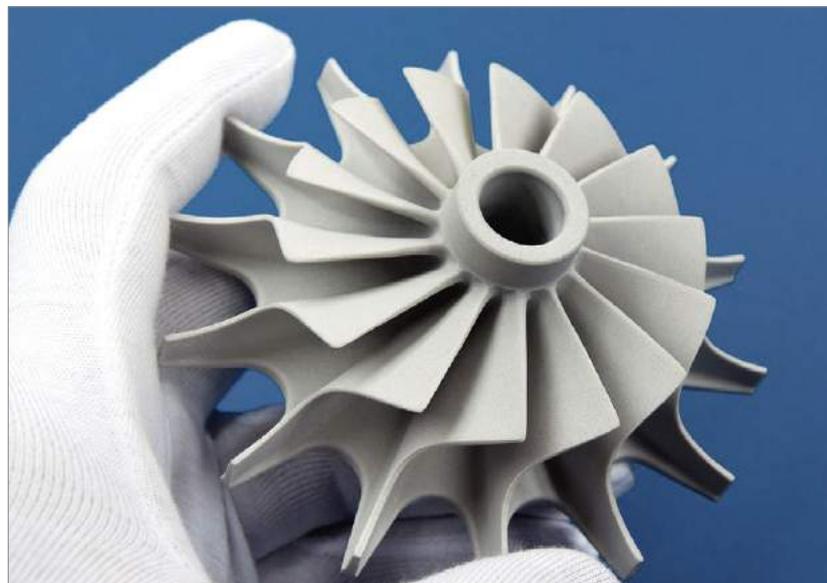
The arrival of production-ready 'MIM-like' metal Additive Manufacturing technologies is today opening up a new world of opportunities for MIM producers. As Tassilo Moritz and colleagues from the Fraunhofer Institute for Ceramic Technologies and Systems (IKTS) explain, the same opportunities will soon also be open to CIM producers. In this article, two ceramic AM processes, both based on CIM-like thermoplastic feedstocks, are reviewed and the opportunities and challenges of the processes examined.

In current ceramic manufacturing, each shaping process has been developed and optimised with regard to the perfection of a certain type of ceramic application. Such products must be manufactured cost-effectively, in high volumes and to tight tolerances without any defects or distortions. In addition to the geometry of a component, the required production quantity is a crucial factor when choosing the most suitable manufacturing technology.

In the field of advanced ceramic components, Ceramic Injection Moulding (CIM) has a relatively long history. Invented in the late 1930s, CIM is still - almost eighty years later - the most efficient processing route for the high-volume production of ceramic components with complex geometries. Much research and development was undertaken during the 1970s and 1980s, pushing this technology into financial viability [1]. In the 1970s, growing concerns over energy, the environment and natural resources increased the interest in heat engines, and national

and international attention was focused on the potential application of ceramics. Injection moulding provided a cost-effective method for the mass production of heat engine parts, whose complex shape posed significant manufacturing challenges [2].

Unlike other powder shaping processes, Ceramic Injection Moulding offers a relatively quick and cost-effective route towards the mass production of geometrically complex, net shape components with tight tolerances [3-8]. Tolerances of 0.3% on linear dimensions are the current



*Fig. 1 This CIM radial turbine rotor is made of silicon nitride and demonstrates well the capabilities of the CIM process*

Ceramic Injection Moulding	Additive Manufacturing
<b>Production quantities</b>	
<ul style="list-style-type: none"> <li>• Medium (&gt; 10,000-50,000) and large series production (&gt; 1 million) parts, depending on the tooling concept</li> </ul>	<ul style="list-style-type: none"> <li>• Single component and small series production</li> <li>• Series number may increase in near future up to medium-size production</li> </ul>
<b>Tooling</b>	
<ul style="list-style-type: none"> <li>• Tooling essential and typically expensive</li> </ul>	<ul style="list-style-type: none"> <li>• Tool-free manufacturing</li> </ul>
<b>Geometrical complexity of components</b>	
<ul style="list-style-type: none"> <li>• Suited for complex shaped components</li> <li>• Holes, threads, undercuts, free form surfaces, etc. are possible</li> </ul>	<ul style="list-style-type: none"> <li>• Extremely high geometric complexity</li> <li>• Previously impossible geometrical features can be realised</li> <li>• Design rules depend on the AM method (e.g. supporting structures, shape fidelity, complexity)</li> </ul>
<b>Reproducibility</b>	
<ul style="list-style-type: none"> <li>• High reproducibility</li> </ul>	<ul style="list-style-type: none"> <li>• Dependent on the AM method</li> <li>• So far, not comparable with conventional shaping methods</li> </ul>
<b>Need for post-treatment in the green state (cleaning)</b>	
<ul style="list-style-type: none"> <li>• Negligible</li> <li>• Removal of the sprues</li> </ul>	<ul style="list-style-type: none"> <li>• Significant effort required to clean components, depending on the AM method (powder removal, rinsing, trimming, etc.)</li> </ul>
<b>Reliability</b>	
<ul style="list-style-type: none"> <li>• High-performance components</li> </ul>	<ul style="list-style-type: none"> <li>• Parts may be less reliable than those using conventional shaping processes, as most ceramic AM methods are in the development stage</li> </ul>
<b>Limitations in applicability</b>	
<ul style="list-style-type: none"> <li>• Material independent</li> <li>• Approximate value of powder particle size &gt; 100 nm, &lt; 40 µm</li> <li>• Particle shape globular; needles or platelets critical</li> <li>• Wall thicknesses &lt; 6-10 mm due to the debinding process</li> </ul>	<ul style="list-style-type: none"> <li>• The ceramic material determines the AM method</li> <li>• Material- and process-dependent</li> <li>• Wall thickness limited due to debinding process (for AM methods based on thermoplastic feedstocks, comparable to CIM)</li> </ul>
<b>Multimaterial approach</b>	
<ul style="list-style-type: none"> <li>• Combination of different materials by multi component injection molding is state of the art</li> </ul>	<ul style="list-style-type: none"> <li>• So far only few AM methods tested for material combination</li> </ul>

Table 1 Pros and cons of CIM versus Additive Manufacturing

standard in CIM. The shaping method is almost waste-free, because green parts containing defects and injection sprues can be readily recycled.

Moreover, CIM technology allows the combination of different materials with contrasting properties via multicomponent injection moulding. Combinations include electrically conductive and insulating ceramics, stainless steel with zirconia, or differently coloured ceramics.

Furthermore, CIM can be combined with tape casting – also referred to as in-mould labelling – by inserting green tapes in the tool cavity and injecting the ceramic feedstock for a durable material combination [9].

However, as is widely known, the limited flexibility of tooling and the significant tooling costs involved are the main reasons CIM technology is only viable for medium or large production volumes. Small-series or single components cannot be made efficiently by this shaping method.

### Ceramic Additive Manufacturing

In the 1980s, rapid prototyping was first introduced to create three-dimensional solid models, built layer-by-layer from a Computer-Aided Design (CAD) file [10]. Today, almost forty years later, Additive Manufacturing processes show significant advantages, including an unprecedented level of design freedom and a tool-free building process. Thus, AM has become attractive for single component and small-series production. Furthermore, AM technologies are very resource-efficient, because only the minimum amount of material required for the part and, where necessary, for the support structures, is used.

A further significant advantage of AM is that both the geometry of a component and its inner structure can be optimised by simulation prior to the building process. The use of AM for rapid prototyping and for rapid tooling has been recognised for a considerable time [11]; the technology has been successfully

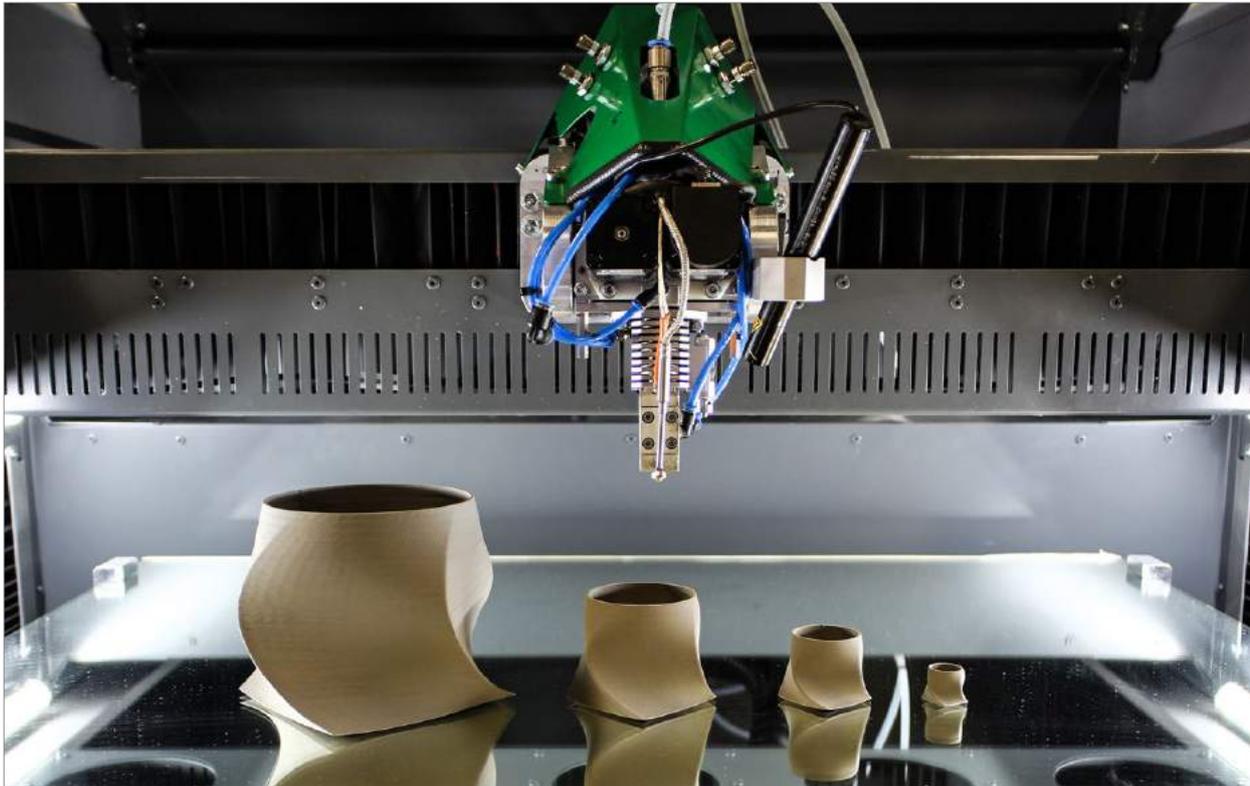


Fig. 2 A Fused Filament Fabrication (FFF) machine with components made from SiC/SiC filaments

applied in numerous fields and has been classified by ASTM F42 [12] into seven processes, as listed below:

- Material Extrusion
- Vat Polymerisation
- Binder Jetting
- Material Jetting
- Powder Bed Fusion
- Sheet Lamination
- Directed Energy Deposition.

In addition to this classification, the AM of ceramic components can be divided into methods applying a material layer-wise, line-wise or droplet-wise. Moreover, when considering the state of the initial material for the building process, these methods can be differentiated into powder bed-based and suspension-based or feedstock-based methods. The latter also include inks, slurries and pastes as initial materials.

This simple classification into only two classes allows a reference to a very important property of the initial materials that defines

the final properties of a ceramic component – the homogeneity of the particle distribution. The particle packing density in powder bed-based AM processes, such as Binder Jetting and Laser-Beam Powder Bed Fusion (LB-PBF), is commonly lower and much less homogeneous than the particle configuration in a suspension, in an ink or in a thermoplastic feedstock. This is because of the much higher dispersion state of well-dispersed particles in a liquid or a molten thermoplastic binder. For this reason, ceramic parts made by powder bed-based methods are difficult to densify to full density in the absence of any liquid phase during sintering. These components often contain a certain porosity; however, this can be an advantage for applications such as filters, catalyst supports or bone replacement parts. On the other hand, suspension- or feedstock-based AM methods, in principle, allow the attainment of highly densified ceramic parts with more

than 99% theoretical density.

In comparison to the AM of metals or polymers, the above-mentioned processes for ceramic components are at a relatively early stage of development. One main reason for this is that ceramics are not ready for use directly after the AM building process, but need a sophisticated thermal post-processing, namely debinding and sintering, to reach their final properties.

### CIM vs Ceramic Additive Manufacturing

All of the outstanding advantages of AM routes for ceramic components raise the question as to whether ceramic AM will compete with more conventional shaping methods, especially with Ceramic Injection Moulding. Table 1 shows a comparison between the pros and cons of AM and CIM.

Two feedstock-based AM methods, Ceramic Fused Filament Fabrication (CerAM FFF, Fig. 2) and Ceramic



Fig. 3 View of an opened infrared heater consisting of a zirconia housing and an embedded stainless steel meandering conductive structure. Due to sintering under a hydrogen atmosphere, the colour of the zirconia turns to black

Thermoplastic 3D Printing (CerAM T3DP), are introduced here as having much in common with Ceramic Injection Moulding. Both methods can be regarded as close relatives of CIM from the viewpoint of the composition of the initial materials. Advantageously, both processes can be easily implemented in existing Powder Injection Moulding production settings, using the same feedstock preparation machines and expanding the potential range of products through, for example, individualisation or personalisation.

Thanks to the fact that both feedstock-based AM methods use

thermoplastic binder systems as the matrix for the ceramic powders, they benefit from a strong change in viscosity by changing temperatures, i.e. the softened or molten feedstock solidifies by cooling. This behaviour provides an almost material-independent processability, meaning that not just any kind of ceramic, but also glass, hardmetal or metal powders can be processed using these AM methods. In other words, all powders that can be processed by CIM can also be used for CerAM FFF or CerAM T3DP.

Another advantage of these two AM methods is also well-known from CIM practice. Different

materials can be combined by these shaping technologies, allowing for multi-material approaches and hybridisation of different methods. Due to the thermoplastic softening of the feedstocks, both material components can be joined in the shaping process, resulting in perfect, mechanically stable green parts. However, for the attainment of the final compound properties, a debinding and sintering step is indispensable. Fortunately, the same debinding equipment used in the CIM industry can also be used for components made by CerAM FFF and CerAM T3DP.

### Ceramic Fused Filament Fabrication (CerAM FFF)

The first AM process considered here in more detail is CerAM FFF, the Fused Filament Fabrication of ceramic components. FFF is known as a direct AM method, applied so far to thermoplastics, such as PLA, ABS, PC or slightly particle-filled modifications. For this process, filaments are used as semi-finished products and are melted and deposited by a heatable nozzle. Comparatively cheap devices are commercially available for this AM process, providing large building platforms, and the building process is quite fast. For CerAM FFF, the thermoplastic filaments are filled with 45-60 vol.% of ceramic powder. This high solid content is necessary for a complete densification of the ceramic components after debinding and during sintering, and is comparable to the solid loading of CIM feedstocks. Furthermore, the homogeneity of powder particle distribution in the FFF feedstock should be as high as in an injection moulding feedstock, although the mechanical flexibility of an FFF feedstock must be higher than is common for CIM feedstocks, due to the spooling of the filaments. The base binder composition is nearly the same and can be easily adjusted to the needs of the CerAM FFF.

The binder matrix contains thermoplastic polymers which provide

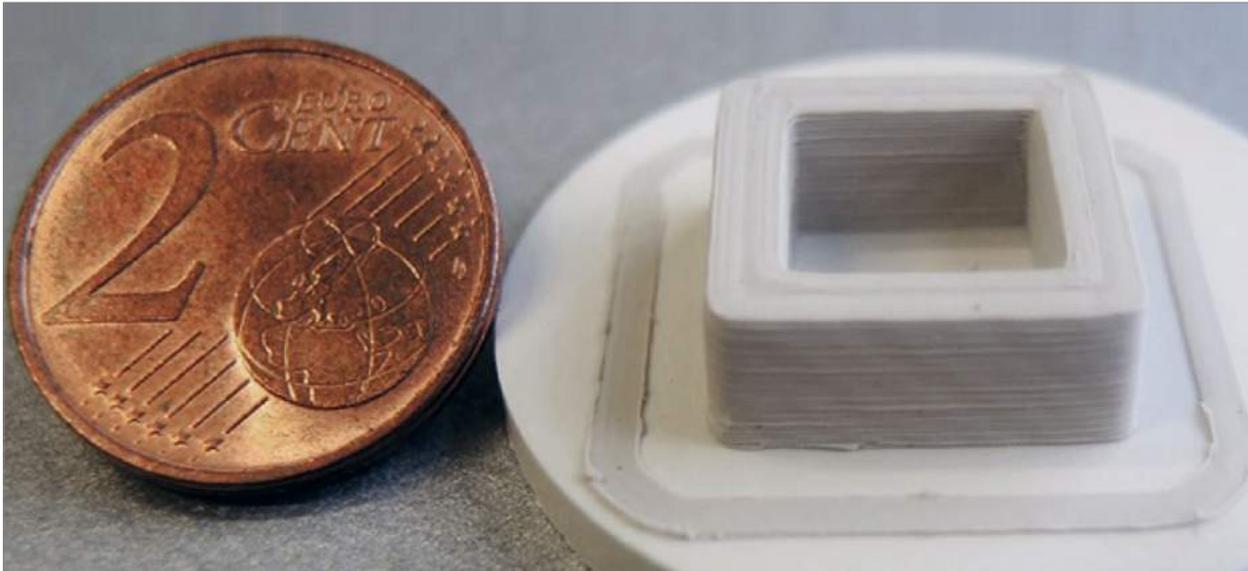


Fig. 4 A CerAM FFF structure assembled on the surface of a CIM part

(i) a certain flexibility for spooling, (ii) a stiffness to be pushed through a heated nozzle and (iii) a high viscosity drop during melting [13]. To manufacture the feedstocks, the same equipment as found in CIM feedstock preparation can be used, for example a twin-screw extruder for smaller batches or a shear roller for larger amounts of feedstock. The similar feedstock preparation process is one of the most important advantages of this AM technology for companies that are already familiar with CIM. The twin screw extruder can be used simultaneously for both feedstock preparation and drawing filaments with diameters of 1.75 mm or 2.85 mm, which may be applied in standard FFF devices.

The authors work with a machine type 140L (HAGE, Austria) as shown in Fig. 2. This device is equipped with a special printing head, where the filament is directly belt driven. In the scope of the European Project CerAMufacturing (GA no. 678503), the machine has been fitted with a second printing head and a two-component FFF process has been developed to produce parts that combine zirconia and 17-4 PH stainless steel (Fig. 3).

Through the selective application of materials via the various print heads, diverse material and property

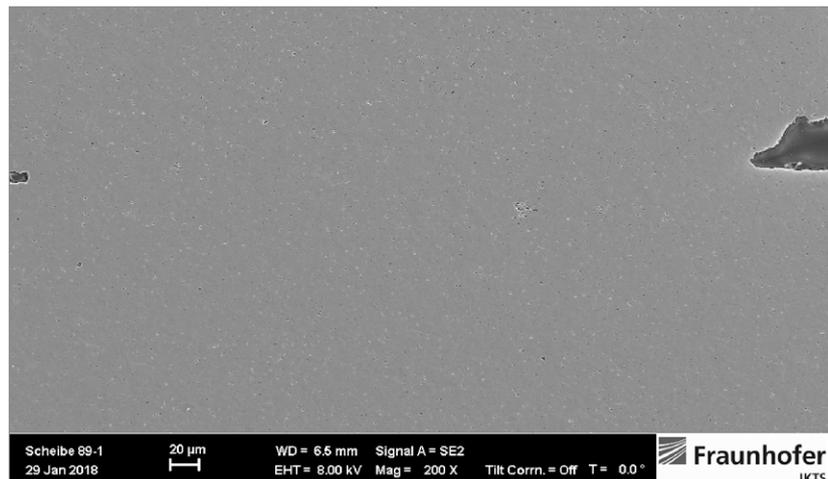


Fig. 5 A FESEM image of a cross-section of the interphase between the injection moulded base plate and the filament. The notch on the right marks the transition zone between the CIM part (below) and the CerAM FFF material (above)

gradients can be produced in the part. The relatively low resolutions associated with this method are compensated by the very large build chamber of 700 x 500 x 400 mm, high productivity and wide range of materials that can be deposited. In addition, ceramic fibres of different lengths can be integrated into the filaments to enable the Additive Manufacturing of CMCs.

Moreover, due to the similarity of the thermoplastic feedstocks, CerAM FFF can be combined with CIM for the

individualisation or personalisation of large-series components by simply building a complex additively manufactured structure onto an injection moulded semi-finished part. In the scope of a project (ZF407641EB6) funded by the German Federal Ministry of Economic Affairs and Energy, this process hybridisation has been developed for the combination of an injection moulded alumina part and alumina filaments applied onto this CIM part via CerAM FFF (Fig. 4). A cross-section of the sintered

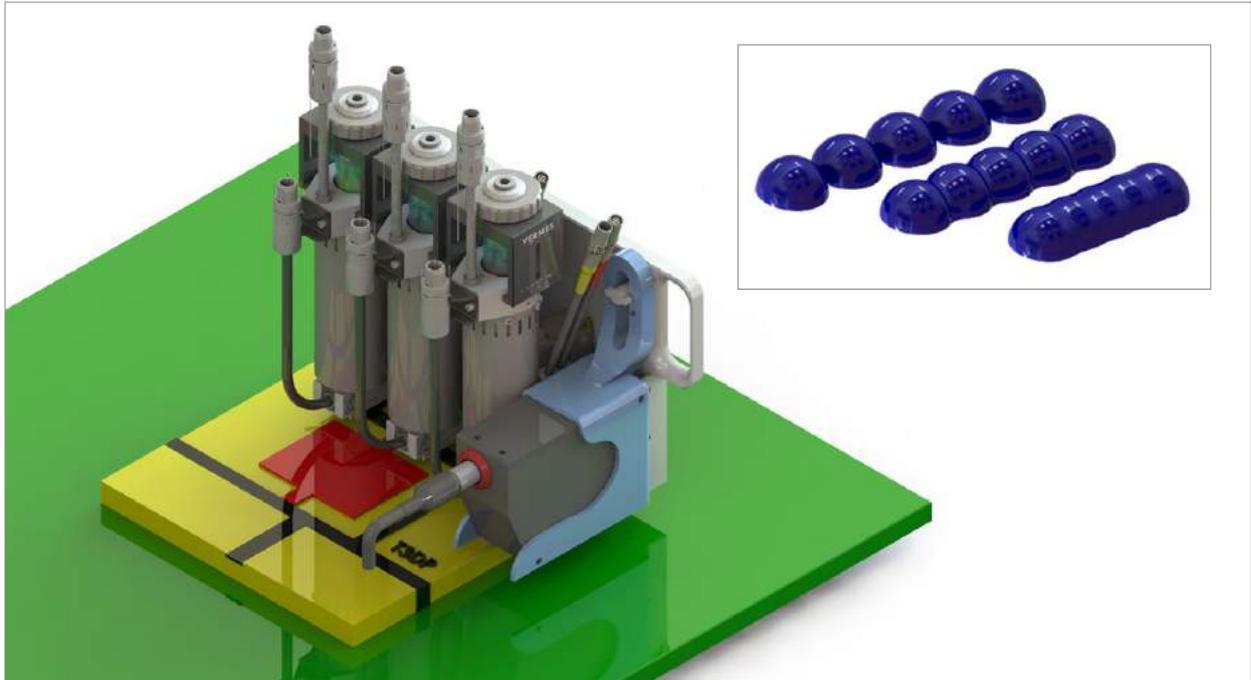


Fig. 6 Array of four micro dispensing units for CerAM T3DP (left) and building principle of this method (inset) (Schematic view)



Fig. 7 Black and white zirconia combined in a test part by CerAM T3DP

hybrid part (Fig. 5) shows a very homogeneous transition between the injection moulded (lower section) and additively manufactured components (upper section). The only marker of the differently manufactured zones is the notch on the right hand side where the filament came into contact with the injection moulded surface.

### Thermoplastic 3D printing (CerAM T3DP)

This second process is closely related to Low Pressure Ceramic Injection Moulding (LP-CIM) as the suspension composition is based on wax. Thus, the viscosity of the thermoplastic suspension is much lower than the

viscosity of a thermoplastic filament or a CIM feedstock and can be processed at around 100°C. In this AM process, the components are built up drop-wise by means of a micro-dispensing unit which works on the drop-on-demand principle. The nozzle orifice diameter can be 100, 160, 200 or 300 µm and the deposition frequency applied for the thermoplastic ceramic suspension is 80-120 Hz.

Depending on the solid loading, the viscosity, the surface tension and the wetting behaviour of the suspension, droplets with diameters between 250-800 µm can be deposited. As with CerAM FFF, CerAM T3DP can also be used for all materials that can be processed by LP-CIM, including all types of ceramics and glass powders as well as metal or hardmetal powders. The powder particle diameter can range from a typical submicron powder up to 5 µm. By adjusting the distance between the individual droplets, overlapping occurs, and line structures are attained. In contrast to ink-jetting, the deposited droplets do not dry – they solidify by cooling,

and the built components must be debound afterwards. No additional curing is needed.

Typical solid contents of CerAM T3DP suspensions are 30-60 vol.%. Mixing and homogenisation of the thermoplastic suspensions takes place in high-speed mixers or, for larger batches, in heated ball mills. Debinding is carried out, as with LP-CIM parts, in a powder bed, which is necessary for the soaking up of the liquefied binder released from the parts during heating in the debinding furnace. Because wax does not decompose in the solid state, but melts before decomposing, the binder must be absorbed by the capillaries of the powder bed. Subsequently, the components are sintered, in common with all ceramic materials.

Depending on the number of micro-dispensing units, one, two or more different suspensions may be deposited, either in one layer or alternating from layer to layer (Fig. 6). Thus, multi component parts can be built or supporting structures made of pure thermoplastic binder, which can be easily removed during the debinding step, may be added. Moreover, sacrificial material can be deposited together with the desired material for the production of closed structures or channels. Furthermore, sacrificial material may be used as a pore-forming agent, which allows for the creation of dense and porous structures in one component.

In the European Project CerAMufacturing, 17-4PH stainless steel was combined with zirconia for the development of a micro-surgical gripper, and black and white zirconia were used for the manufacture of an individualised watch bezel (Fig. 8). Manufacturing multi component parts requires the careful selection of materials with a comparable coefficient of thermal expansion, in order to be successfully processed in the same sintering conditions, namely sintering temperature, atmosphere and pressure. Moreover, the shrinkage behaviour must be adjusted very precisely, as the same total shrinkage must be achieved by both components. A more detailed

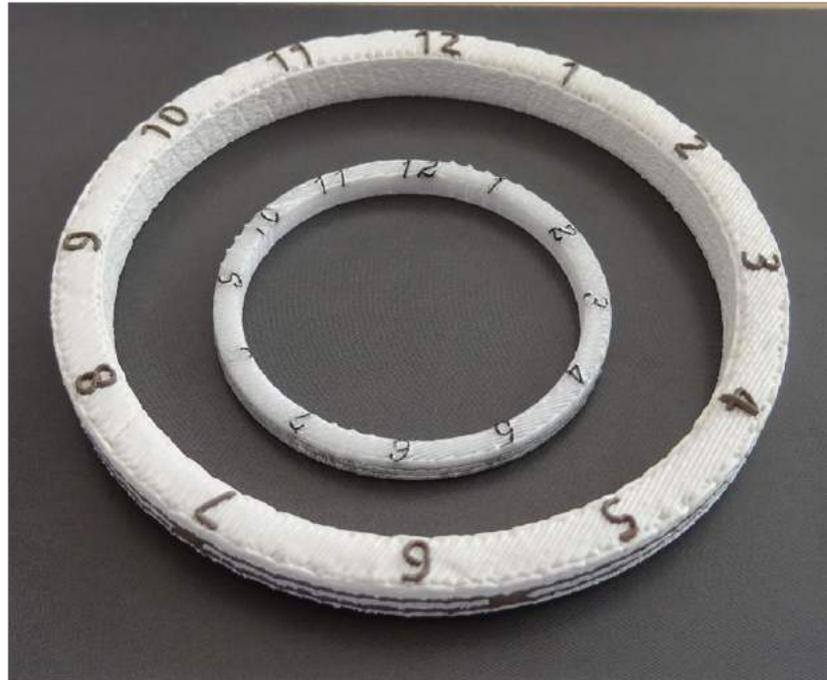


Fig. 8 Black and white zirconia combined in a testing part by CerAM T3DP

description as to how this may be achieved is given in [9, 12].

Again, as already demonstrated for the CerAM FFF process, CerAM T3DP can be used to combine large series CIM parts with Additive Manufacturing for the personalisation or individualisation of components, especially with components made by LP-CIM, due to the relationship of the binder constituents. The very same feedstock may be used for both LP-CIM and CerAM T3DP, but series parts, which must always have the same dimensions with high reproducibility, can be made much faster and more precisely by LP-CIM. Nevertheless, CerAM T3DP can be accelerated for the rapid production of larger components by increasing the frequency from droplet deposition up to jetting. Thus, this method would also allow for filling tool cavities or cavities built by supporting material first.

## Conclusions

Additive Manufacturing processes allow for the manufacture of ceramic components with a geometrical complexity which could never be

attained by means of conventional shaping routes or subtractive processes. They are cost- and resource-saving technologies, as they are both tool-free and only use materials where they are really needed. On the other hand, AM methods also have limitations that include the choice of materials that they can be applied to, achievable tolerances or feasible structural resolutions and details.

For ceramics in particular, AM processes are at an early stage of development, and much work still has to be done to transform them into reliable and productive shaping routes. However, there are some opportunities, not least for companies which are already experienced in thermoplastic shaping processes such as CIM or LP-CIM. Thermoplastic AM processes such as CerAM FFF and CerAM T3DP require the same equipment for feedstock preparation as CIM does. With a shear roller and a twin-screw extruder, a company can produce both feedstocks for CIM and filaments for CerAM FFF. The debinding and sintering of the green components remains exactly the same as is applied to CIM or LP-CIM.

Existing experience and knowledge can therefore be applied to these new technologies without the need for expensive employee training. From this point of view, both of the highlighted AM methods can be a valuable add-on for CIM part producers to existing in-house production process, and may help to widen the spectrum of products or enable the manufacture of new customised components in the future. Not least, the combination of AM and conventional processes will help save tooling costs, reduce lead times and manufacturing development costs for individualised or personalised products.

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Vol. 3 No. 1 SPRING 2017

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Vol. 4 No. 1 SPRING 2018



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# Euro PM2018: Innovations in Metal Injection Moulding highlighted in Bilbao

A number of technical papers presented at Euro PM2018, organised by the European Powder Metallurgy Association (EPMA) and held in Bilbao, Spain, October 14-18, 2018, addressed processing and compositional developments in Metal Injection Moulding. In this report, Dr David Whittaker reviews four papers that cover Lost-Form PIM, an innovative debinding and sintering process, the MIM of Ti-6Al-4V HDH powder with the addition of yttrium, and the use of iron as a low-cost sintering aid for Ti-6Al-7Nb.



## Lost-Form Powder Injection Moulding - combining Additive Manufacturing and PIM

A paper by Sebastian Boris Hein and Anna-Lena Otte (Fraunhofer IFAM, Bremen, Germany) described the development of a novel process which has been named 'Lost-Form Powder Injection Moulding' [1]. This process combines PIM with Additive Manufacturing (AM) by producing sacrificial mould inserts from a suitable polymer and incorporating these inserts into PIM moulds.

The keys to the success of this approach were deemed to be to create the 3D printed polymer insert with sufficient mechanical strength to withstand the high pressures and temperatures involved in injection of the PIM feedstock around it, and for such an insert to respond acceptably to the process stages of solvent and thermal debinding.

The resin for the 3D printing of Lost-Form inserts was provided by Dreve Prodimed (FotoDent® cast).

The printing of the inserts was carried out on a DLP (Digital Light Processing) printer. Fig. 1 shows the design and an example of the insert in the form of a lattice structure with a double layer of interconnected voids in the form of truncated cuboctahedra.

The powders used to create the feedstock for the reported study were 316L stainless steel (80% < 5 µm) and zirconia (TZ-3Y-E, DV 50 ~ 0.66 µm) at 50/50 volume fractions. Binders for the feedstock were based

on a classic polyolefin/wax system (PE-wax), as well as a plasticised elastomeric polyamide (PA).

The binder components and powders were mixed in the desired fractions and then kneaded at elevated temperatures (approximately 120°C–170°C, depending on the binder system), with the binder system consisting of a mixture of plasticisers, polymer and surfactant if necessary. Due to continued kneading during the cooling step, the feedstock formed granules and was directly

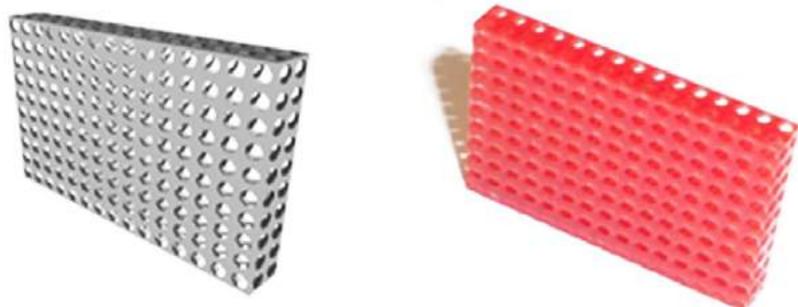


Fig. 1 Design of the Lost-Form insert (left) and the printed part (right) [1]

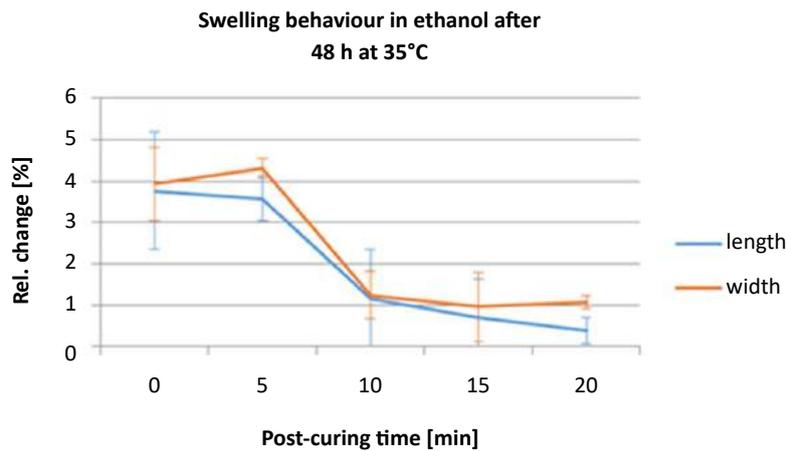


Fig. 2 Diagram of the swelling behaviour of AM parts in ethanol [1]

usable for injection moulding. The injection moulding step was carried out on a plunger injection moulding machine, with the printed part inserted into the mould. The next step was solvent debinding, during which the soluble components are extracted from the green part. The resulting brown part, which still consisted of the printed part and the remaining feedstock components, was then placed in a furnace where the printed part and the remaining organic binder components were decomposed thermally prior to the subsequent sintering step. All materials were sintered at 1350°C under a hydrogen atmosphere.

In solvent debinding, the goal is to remove soluble binder components in order to introduce porosity in the part. Suitable solvents depend on the employed binder system. For the PE-wax binder, n-hexane is a typical solvent, while, for the PA-based binders, acetone and ethanol can be used. Therefore, an early question in the development of the Lost-Form PIM process was how the printed parts behaved when immersed in these solvents. What was observed was a swelling of the printed parts in acetone and less so in ethanol, whereas no swelling occurred in n-hexane.

As a different swelling behaviour of the printed part and the feedstock would lead to mechanical stress of the joint between them, the influence of post-curing of the printed parts

on the swelling behaviour was also investigated. The underlying idea was that a higher degree of cross linking in the material of the printed part would increase the rigidity of the part and reduce the ability to take up solvent. Fig. 2 shows the part sizes, depending on the post-curing time in UV light, after immersion in ethanol for 48 h at 35°C. As can be seen from this figure, post-curing does have an effect on the swelling of the printed parts, as size change is lower after curing for 10 min compared with shorter curing times or no post-curing at all. Curing times of more than 10 min do not lessen the swelling significantly. Based on this observation, post-curing of the printed parts was deemed to be a reasonable procedure in preventing size changes during solvent debinding.

It was observed that green parts with PE-wax binder could be debound in n-hexane without any visual changes occurring. Debinding of the green parts in ethanol at 35°C, which also removes most of the waxes in the binder, led to the destruction of the feedstock component, as the swelling of the printed part induced cracks in the feedstock. Green parts with the PA-binder, debound in ethanol or acetone at 35°C, were warped directly after the debinding step, but nearly regained their shape after drying overnight. This effect was less severe for green parts that contained post-cured printed parts. The elasticity of

the feedstock could compensate for the warping without crack formation.

The thermal behaviour of the printed inserts during the subsequent thermal debinding step was characterised by simultaneous thermal analysis (STA) in a hydrogen atmosphere. This analysis showed that the main mass loss was between approximately 240°C and 380°C, with 76.5% of the mass being lost in an endothermic process. A second endothermic step followed at approximately 430°C. The onset temperatures for these two steps were calculated to be 242°C and 386°C, respectively. Based on the STA, the thermal debinding was carried out with two holding times, one in the range of the first mass loss step and the other at the onset of the second mass loss step.

The authors argued that, in the thermal debinding step, there are two challenges to be considered with regard to potential damage to the feedstock component. Firstly, the formation of low-molecular decomposition products during the thermal decomposition of the printed insert may occur too suddenly and damage the feedstock part. Secondly, the amount of printed material may be too high to be decomposed cleanly, and lead to carbon-rich residue that can react with the metal at elevated temperatures. This can lead to a carburisation of the steel, which alters its composition and properties and possibly induces the formation of lower melting phases that are liquid at the selected sintering temperature.

Therefore, the temperature profile must be adapted such that the printed material is decomposed completely, but gently enough to avoid damaging the fragile feedstock part. In the case of the PE-wax feedstock, it was observed that all trials led to damaged parts, independent of the process parameters (Fig. 3a). It was concluded, therefore, that there are mechanical stresses during thermal debinding and that the brittle feedstock cannot tolerate these stresses.

With the elastic PA-based feedstock, the situation is more complex. When the temperature of the first debinding step was between 245 and

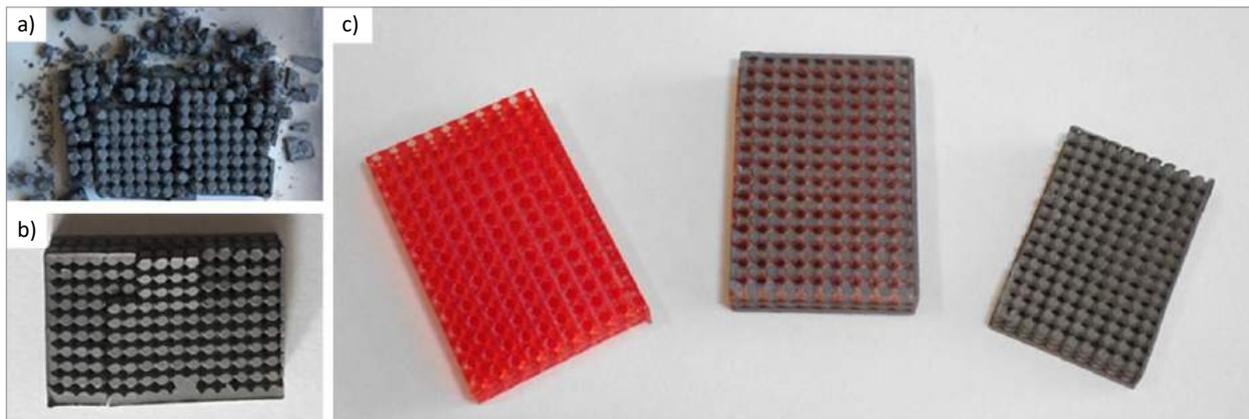


Fig. 3 a) Sintered part with PE-wax feedstock; b) sintered part with PA-based feedstock, thermally debound at 245°C; c) printed part (left), brown part with PA-based feedstock (middle), sintered part (right) [1]

265°C, parts showed little damage (Fig. 3b). At debinding temperatures above 280°C for the first holding step, the parts showed increasing damage. However, there was a large variation in results. Some specimens showed little damage, while others, processed with the same parameters, showed more damage.

As the observed effects grew more intense when printed parts with increased wall thicknesses were used, the authors attempted to reduce the amount of printed material that had to be decomposed thermally by diluting the printing resin with n-butyl acetate, on the basis that a non-reactive, volatile solvent would take up space in the printed part, but would evaporate during the drying of the part. Thus, there would be less mass to decompose, the polymer network would be more wide-meshed, and thermal degradation products would diffuse more easily through the part. This approach produced the best parts, as can be seen in Fig. 3c.

Based on these results, the process was transferred to a different part geometry, namely a cannulated screw nail. The sintered part showed signs of carburisation, observable as molten metallic beads on the surface. Even so, the general feasibility of the Lost-Form PIM process could be demonstrated, but it was concluded that improvements would be necessary for the process to be transferable to industrial production.

Ni	Fe	Cr	Mo	Al	Ti	Nb	C
52.5	19.0	19.0	3.0	0.5	0.9	5.3	0.0

Table 1 Chemical composition in mass percentage of the Inconel 718 powder used in the study [2]

Overall, the authors concluded that the use of the elastic PA binder system offered the best potential process, but, even for this option, the processing window seemed quite narrow for several process steps and optimisation would be necessary in order for the Lost-Form PIM process to work reliably.

For future work, an approach was proposed with chemically cleavable functionalities in the printed part in order to remove it separately, prior to the solvent debinding. Furthermore, the printed parts should be designed more sensibly, e.g. by using segmented cavities, so that the amount of printed material to be removed would be reduced.

### Improving kinetics of MIM process by applying new methods of debinding and sintering

The second paper in this review, from Olivier Dugauguez and Thierry Barriere (Universite de Bourgogne-Franche Comte, France), Andrea Garcia-Junceda (IMDEA Materiales Institute, Spain) and Antonia Jimenez-Morales and Jose Manuel

Torralba (Universidad Carlos III de Madrid, Spain), discussed the use of new processing methods in reducing the time and energy involved in the solvent extraction and sintering process steps for MIM Inconel 718 components [2]. The new processing methods under consideration were, respectively, solvent extraction using supercritical CO<sub>2</sub> fluid and Field Assisted Sintering.

Nickel-chromium superalloys exhibit good mechanical strength and high resistance to creep at high temperatures, in addition to corrosion resistance. Therefore, they can be operated in combined conditions of strength and temperature under the influence of a corrosive medium. The problem with this material type is the difficulty in machining a mechanical part due to its poor ductility, imposing dimensional limits and low material utilisation in obtaining the desired component; hence the interest in processing such materials by Metal Injection Moulding.

The chemical composition of the Inconel 718 powder used in the reported study is shown in Table 1. The particle size distribution was defined according to the diameter values corresponding to

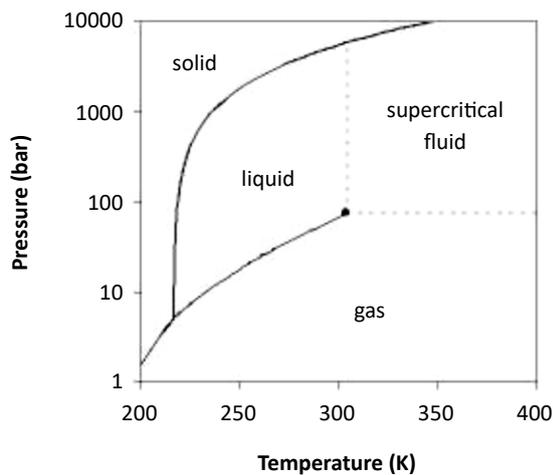


Fig. 4 Phase diagram for carbon dioxide [2]

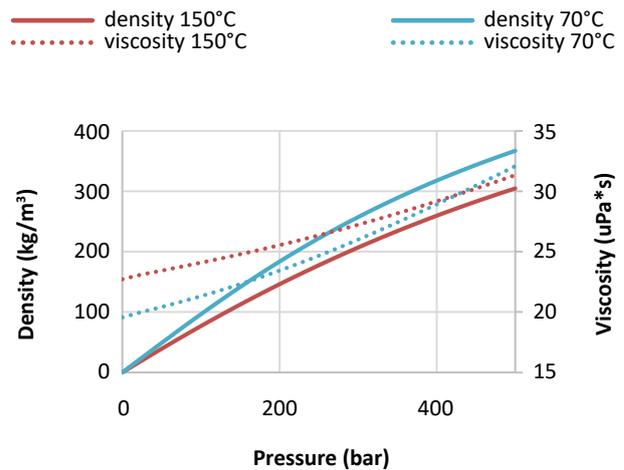


Fig. 5 Evolution of Carbon dioxide properties as a function of pressure [2]

the cumulative volume fractions D10, D50 and D90 as 3.53  $\mu\text{m}$ , 6.24  $\mu\text{m}$  and 10.97  $\mu\text{m}$  respectively. The standard deviation was 0.86  $\mu\text{m}$ . According to published literature, the microstructure of Inconel 718 after sintering is composed of a  $\gamma$  matrix reinforced by a  $\gamma'$  phase  $\text{Ni}_3(\text{Al}, \text{Ti})$  and a  $\gamma''$  phase  $\text{Ni}_3(\text{Nb}, \text{Ti})$ . These two intermetallic phases are responsible for the increase in hardness and good performance of the alloy at high temperature. The carbon content must be limited as much as possible in order to avoid the formation of niobium and titanium carbides.

The binder selected for the feedstock in the study was composed of Polypropylene (PP), Polyethylene Glycol (PEG 20K) and Stearic Acid (SA). The mixing of the binder with the metallic powder was performed in a twin screw mixer. The feedstock was then milled and was injected into green parts in the form of cylinders, using an Arburg 220S machine.

In conventional MIM processing, green parts next undergo a solvent debinding step. They are introduced into distilled water at around 35°C for 48 h, in order to remove the PEG, and are then dried in an oven at 75°C for 2 h. The PP is eliminated by thermal debinding at 500°C for 2 h under an argon atmosphere. A heating temperature rate of 2 K/min is applied during the cycle, in order to avoid overpressure inside the

sample during the degradation of the polymer. After completion of the thermal debinding, the sample is sintered at 1290°C for at least 3 h at a heating rate of 5 K/min. The cooling is done naturally at a rate of 10 K/min. In order to improve the mechanical properties of the material, a thermal treatment is applied, consisting of annealing at 980°C for 1 hr and aging successively at 720°C and 620°C for 8 h. This treatment allows the diffusion of the hardening phases  $\gamma''$ . In total, these steps take around 80 h. The solvent debinding is the step that takes most of the time, due to the time the water needs to extract the PEG.

In order to reduce the time involved in solvent debinding, the use of a supercritical fluid was assessed. The supercritical state of a fluid can be reached at a certain temperature and pressure, called the triple point. The conditions for  $\text{CO}_2$  are 304.1 K and 73.8 bar. The equipment used was a supercritical extractor. The system was designed to introduce supercritical fluid inside an autoclave at the temperature and pressure desired. The programmed cycles consist of five steps: first, the  $\text{CO}_2$  is cooled to around 0°C, in order to be liquid. The pressure is then raised via a pump and then the fluid is passed inside a thermal exchanger. The  $\text{CO}_2$  is then introduced into a reaction chamber in the presence

of the green samples and reacts with the polymers within the binder and smoothly begins the extraction process. The fluid mixed with the residues from the polymer is then passed through a separator in order to allow the  $\text{CO}_2$  to follow a recycling line for a new cycle. Once the cycle is complete, the used  $\text{CO}_2$  is purged from the system and the samples removed from the equipment.

The cycle parameters that can be controlled are the temperature and the pressure of the fluid, the time of reaction and the rates of increase and decrease of the pressure. In order to retain the shape of the MIM sample, the pressure is raised to the desired pressure at 10 bar/min and decreased in two steps, from the dwelling pressure at 20 bar/min and then from 90 bar to ambient pressure at a lower speed of 3 bar/min.

This is due to the phase diagram of the  $\text{CO}_2$  (Fig. 4), in relation to the reversion from the supercritical to the gas phase. During this transition, there is a probability of overpressure inside the samples that needs to be avoided. The temperature and pressure applied change the properties of the fluid, such as the density (Fig. 5). The optimisation of these parameters will impact on the kinetics of the test.

The temperature and pressure conditions to obtain the complete extraction of the PEG within the

binder have been found to be 400 bar and 150°C. With these parameters, no external damage has been observed. The next steps in checking the effects of the debinding were to complete the MIM process with thermal debinding and sintering. The same procedure was carried out for a sample debound in water. The microstructure obtained with supercritical debinding was close to that obtained via the conventional route. The main difference that can be observed is at the edges of the samples. The supercritically debound sample showed a well-defined cylindrical shape, while the water debound sample looked less regular.

In order to determine the effect on the surface quality of the samples, roughness analysis has been performed via optical analysis (Fig. 6). In the case of water debinding, the roughness doubled after the sintering treatment and reached an  $R_p$  of 9.27  $\mu\text{m}$  and an  $R_a$  of 3.77  $\mu\text{m}$ . On the other hand, in the case of supercritical debinding, the roughness has been limited to an  $R_p$  of 6.03  $\mu\text{m}$  and an  $R_a$  of 2.21  $\mu\text{m}$ . The strong increase of roughness in the case of the water debinding can be explained by a much longer immersion time in the solvent, leading to a modification of the rigidity of the component. The result was a surface more damaged by the debinding process and amplified after the thermal treatments. As the fluid in the supercritical state diffused inside the MIM sample in a manner more similar to a gas, the sample was less damaged with a better final surface finish.

Field Assisted Sintering is a hot pressing technique in which pressure and an electrical field are simultaneously applied to the workpiece material through graphite punches, covered with tungsten foil to avoid carburisation. In the reported study, samples have been consolidated in a Gleeble 3800 system by the application of a strong electric current passed through the punches under vacuum. The temperature of the samples was measured via two thermocouples,

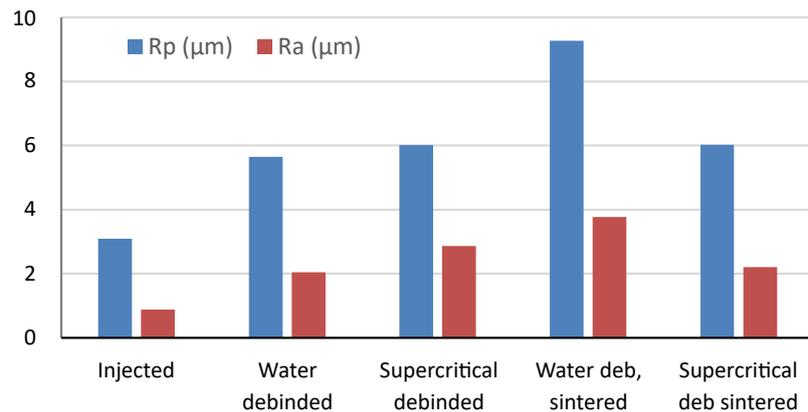


Fig. 6 Surface roughness results after each of the treatments applied to the MIM samples [2]

one at the centre of one of the punches and the second close to the powder inside the graphite die. The shrinkage of the sample was measured via the displacement of the punches (Fig. 7). The heating rate of the sample was fixed at 100K/min, a dwell time was applied at 800°C combined with the application of a pressure of 10 MPa and this pressure was maintained until cooling was completed.

After debinding, the MIM samples were extremely brittle and had to be carefully manipulated. In order to use them in the Gleeble system, the samples were sintered at low pressure (10 MPa). A density of

98.8% was obtained at a temperature of 1250°C, maintained for 15 min. Natural cooling was applied after sintering. The hardness achieved was 253±11 HV. A fine microstructure was obtained with a mean grain size of 6.2  $\mu\text{m}$ .

EDX analysis (Fig. 8) provided information on the phases present within the sintered material. Zone 1 had a composition close to the initial composition of the powder, corresponding to the matrix of the material. Electropolishing revealed white grains at the surface of the material present within the grains and at grain boundaries. These were mainly composed of niobium and nickel.

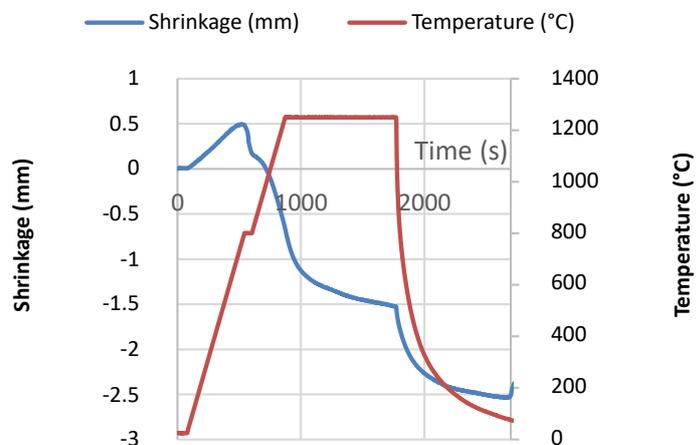


Fig. 7 Field Assisted Sintering of an Inconel 718 MIM sample at 1250°C for 15 min and under 10 MPa pressure [2]

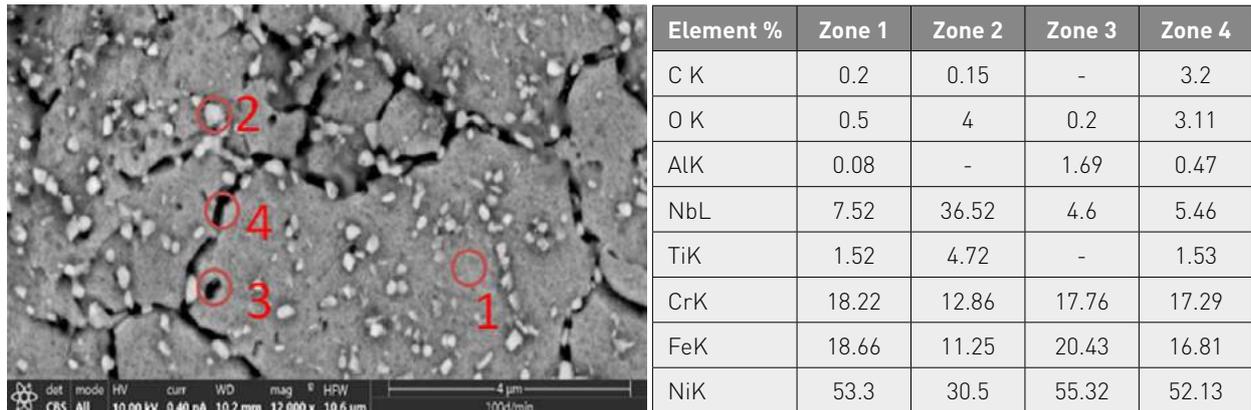


Fig. 8 SEM observation and EDX analysis of a MIM sample sintered with a heating rate of 100°C/min, a dwell at 1250°C for 15 min and a pressure of 10 MPa [2]

There is a strong possibility that these grains were δ phase, as the hardness of the sample was close to that after sintering in a furnace. Some black phases were also present inside the grains containing significant amounts of aluminium. These were more probably γ phases. Finally, a strong presence of carbon was found at the grain boundaries, meaning that carbides were present within the samples.

The authors drew the overall conclusion that debinding by CO<sub>2</sub> in a supercritical state showed interesting results, reducing solvent debinding times from fifty hours to only six, and even improving the surface finish of the samples, reducing the need for post-treatment. With regard to Field Assisted Sintering, the sintering can be completed in 40 min. Thanks to a fast heating rate and a low dwelling time, the microstructure showed a much finer grain size, with a consequent improvement in mechanical properties. The use of these two methods could lead to an

improvement of the kinetics of the MIM process while improving the quality of the samples produced.

### MIM of Ti-6Al-4V HDH powder with high oxygen content, achieving high strength and ductility by the addition of yttrium

The remaining two papers reviewed were both submitted by the research group at the Helmholtz-Zentrum Geesthacht Institute of Materials Research, Germany, and addressed the MIM of titanium alloys.

The first of these papers came from Wolfgang Limberg, Regine Willumeit-Roemer, Florian Pyczak and Thomas Ebel and presented a study of the use of an addition of yttrium to achieve high strength and high density and enable the use of a Ti-6Al-4V hydride-dehydride (HDH) powder with high initial oxygen content [3].

For Ti-6Al-4V grade 5, which is the most commonly used titanium alloy, ASTM Standard B348 requires a minimum plastic elongation of 10%. For the production of titanium alloy MIM parts with high ductility, low oxygen content is essential. An elevated oxygen content leads to an increase in tensile strength, but, when the oxygen content exceeds a critical value of ~0.32 wt.%, tensile elongation decreases dramatically. The oxygen content of MIM-processed titanium parts depends largely on the initial purity of the alloy powder used. The oxygen content of cheap powders, such as HDH titanium alloy powders, often exceeds the critical value, but alloy powders with low oxygen content, such as gas atomised or plasma atomised powders, are expensive.

Yttrium has the highest capability for scavenging of oxygen and recently reported work has shown that pure yttrium added to MIM-processed Ti-6Al-4V seems to be able to scavenge oxygen from titanium by in situ formation of Y<sub>2</sub>O<sub>3</sub> during sintering, leading to an increased ductility. This would facilitate the usage of cheap HDH Ti powder with high oxygen content for the production of MIM titanium alloy parts, while avoiding the associated embrittlement. The aim of the study was to observe the capability of yttrium to decrease the oxygen content in the titanium lattice of high-oxygen loaded Ti-6Al-4V powders by scavenging of oxygen by the in situ formation of Y<sub>2</sub>O<sub>3</sub> during the sintering process.

Feedstock name	Powder composition [wt.-%]			Binder content [wt.-%]
	HDH Ti-6Al-4V	Plasma atomised Ti-6Al-4V	Yttrium	
PA		100		10
HD	80	20		12
HDY	79.6	19.9	0.5	12

Table 2 Powder composition and binder contents of the feedstocks assessed [3]

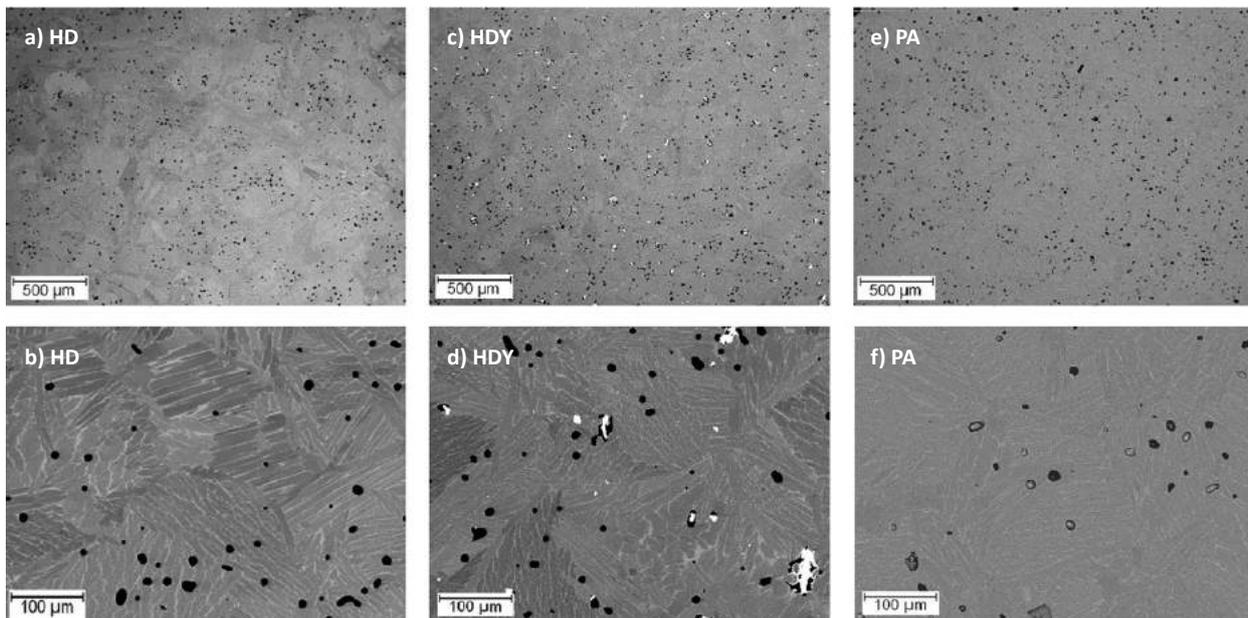


Fig. 9 SEM images of cross section of the various MIM-processed Ti-6Al-4V samples [3]

In the reported investigations, two different Ti-6Al-4V powders were used. The first was HDH powder with a particle size  $d < 45 \mu\text{m}$  and angular shape. The oxygen content of this powder was analysed as  $4200 \mu\text{g/g}$  and the nitrogen content was  $170 \mu\text{g/g}$ . The other Ti-6Al-4V alloy powder used was a plasma atomised Grade 5 powder with a particle diameter  $< 45 \mu\text{m}$ . The powder particles were spherically shaped with a smooth surface. Melt extraction analysis of this powder showed an oxygen content of  $1600 \mu\text{g/g}$  and a nitrogen content of  $200 \mu\text{g/g}$ .

The yttrium powder used was a commercially available powder with a purity of  $> 99.9\%$ . The shape of the yttrium powder particles was square-edged with a rough and craggy surface. Particle size was  $< 45 \mu\text{m}$ . Both the oxygen content ( $9100 \mu\text{g/g}$ ) and the nitrogen content ( $8350 \mu\text{g/g}$ ) of the yttrium powder were much higher than those of the two Ti-6Al-4V powders. The binder used contained 35% ethylene vinyl acetate (EVA), 60% paraffin wax (PW) and 5% stearic acid (SA).

The entire powder handling was performed in a glove box under argon atmosphere to prevent the fine powder from further oxidation.

A gas purifier eliminated the residual oxygen in the argon atmosphere, so the oxygen content in the glove box could be kept below 1 ppm.

Three types of feedstock were prepared, the composition of the powders being listed in Table 2. The first feedstock was the standard Ti-6Al-4V feedstock, a mixture of 90 wt.% plasma atomised (PA) Ti-6Al-4V powder and 10 wt.% of the binder. This feedstock with low oxygen content was for comparison with the high oxygen loaded HDH feedstocks.

For the second feedstock, called 'feedstock HD', a powder mixture consisting of 80% HDH Ti-6Al-4V powder and 20% plasma atomised Ti-6Al-4V powder was used. The third feedstock (HDY) had the same ratio of HDH Ti-6Al-4V to plasma atomised Ti-6Al-4V powder as feedstock HD but with the addition of 0.5 wt.% yttrium powder. Due to the rough and craggy surface of the HDH powder particles, the flowability of this powder was very low. This was the reason for the addition of 20 wt.% of the plasma atomised powder with smooth surfaced particles to the HDH powder. However, the enhancement of the flowability by that addition of the plasma atomised Ti-6Al-4V was still rather low. Therefore, the binder content for the two HDH powder

based feedstocks was increased from 10 to 12 wt.% to ensure sufficient flowability for injection moulding.

The Ti-6Al-4V powders and the yttrium powder were mixed in a planetary mixer for four minutes at a speed of  $2000 \text{ min}^{-1}$  to break up particle clusters and achieve a homogeneous dispersion. The feedstocks were then prepared by mixing Ti-6Al-4V alloy powder, yttrium powder and binder in a double Z-blade mixer for 2 h at a temperature of  $120^\circ\text{C}$ . After solidification, the feedstock was granulated by means of a cutting mill.

For tensile tests, standard MIM specimens, according to ISO 2740, were injection moulded, using a two-cavity mould on a conventional Arburg 320S 500-60 injection moulding machine. An injection pressure of 800 bar, an injection rate of  $35 \text{ cm}^3/\text{s}$ , an injection temperature of  $112^\circ\text{C}$  and a mould temperature of  $43^\circ\text{C}$  proved to be adequate parameters for the injection process.

Solvent debinding was then performed using hexane at  $40^\circ\text{C}$  for 15 h and thermal debinding and sintering were performed in subsequent steps, using a cold-wall furnace with molybdenum heating elements and molybdenum shield packs. The thermal debinding took

	PA	HD	HDY
Initial porosity [%]	33.9	38.6	38.6
Residual porosity [%]	2.6	1.2	1.9

Table 3 Initial and residual porosities of the sintered parts [3]

	HDH Ti-6Al-4V	Plasma atomised Ti-6Al-4V	Yttrium
Oxygen content [ $\mu\text{g/g}$ ]	4200	1600	9100

Table 4 Oxygen concentrations in the powders used [3]

	PA	HD	HDY
Initial concentration of powder	1600	3680	3706
Concentration of sintered parts	1940	4154	4178
Oxygen pick up	340	474	481
Oxygen scavenged by Y	-	-	1300
Concentration in Ti-lattice	1940	4154	2878

Table 5 Oxygen concentrations (in  $\mu\text{g/g}$ ) in the initial powder mixtures and sintered parts [3]

place under a slight argon flow of 150 U/h at 5 mbar in a temperature range between 250 and 400°C. Sintering was carried out at a temperature of 1400°C for 2 h under vacuum atmosphere ( $10^{-5}$  mbar) with heating at 5 K/min and cooling at 10 K/min.

Fig. 9 shows SEM images (BSE-mode) of cross-sections of the sintered tensile test specimens of Ti-6Al-4V with and without an addition of yttrium powder. The microstructure consisted of lamellar  $\alpha/\beta$  colonies. The  $\alpha$ -lamellas are imaged dark grey, while the  $\beta$ -phase between the  $\alpha$ -lamellas is visible in light grey. The pores are visible as black dots. In contrast to the pure Ti-6Al-4V (HD and PA) samples (Fig. 9 a-b and e-f), the specimens produced with powder containing 0.5 wt.% yttrium (HDY), show many large pores and some pore clusters with sizes up to 75  $\mu\text{m}$  (Fig. 9d), partially filled with a white phase. EDS-analyses have shown that these white phases are  $\text{Y}_2\text{O}_3$  particles, which formed during the sintering process. Single small  $\text{Y}_2\text{O}_3$  particles with a size of a few micrometres were also found in the titanium matrix

between the pores. It was assumed that only a small amount of yttrium was dissolved before reacting with the oxygen dissolved in the titanium lattice. The majority of the yttrium oxidises before it can be dissolved in the titanium.

The residual porosities of the sintered specimens are listed in Table 3. The initial porosity of the pure plasma atomised Ti-6Al-4V parts (PA) before sintering was 33.9%, caused by the binder content of 10 wt.% in the feedstock. After sintering at 1400°C, the residual porosity was determined to be 2.6%. For the parts, which were produced using a powder mixture of 20% plasma atomised powder and 80% HDH-powder (HD), the feedstock contained 12 wt.% binder. This led to an initial porosity of 38.6% before sintering. In spite of this higher initial porosity, compared with the parts produced with the PA-feedstock, these parts showed a residual porosity of only 1.2% after sintering. This higher densification was probably caused by the higher specific surface of the irregular-shaped HDH powder particles, leading to a higher sintering activity. The addition of 0.5 wt.%

yttrium to the powder mixture of 20% plasma atomised powder and 80% HDH powder (HDY) led to an increase of residual porosity to 1.9% after sintering.

The oxygen concentrations of the alloy powders and the yttrium powder are listed in Table 4. Table 5 shows the initial oxygen concentrations of the different feedstocks, calculated using the values from Table 4 and the powder compositions from Table 2. The second line of Table 5 shows the measured oxygen concentrations of the MIM-manufactured specimens after sintering and the third line shows the oxygen pick up during sintering.

The increase in oxygen content of plasma atomised Ti-6Al-4V powder (PA) during MIM-processing was around 340  $\mu\text{g/g}$ . This was 134  $\mu\text{g/g}$  lower than that of the HD-powder mixture. The reason for this difference could be the higher specific surface of the HDH-powder.

The oxygen pick up during sintering of HD and HDY was the same, independent of the yttrium content, the addition of yttrium powder to Ti-6Al-4V powder having no influence on the increase in oxygen concentration during sintering under vacuum.

With reference to the stoichiometry of  $\text{Y}_2\text{O}_3$  and the atomic masses of oxygen and yttrium, 1 g yttrium reacts with 0.27 g oxygen when it fully transforms to  $\text{Y}_2\text{O}_3$ . The 0.5 wt.% of yttrium added to the Ti-6Al-4V alloy mixture therefore needs 0.135 wt.% oxygen, for complete transformation. This results in 1350  $\mu\text{g/g}$  oxygen content in the alloy, bound to yttrium in the form of oxide. Only a minor fraction of this oxygen was introduced into the alloy mixture with the yttrium powder (45  $\mu\text{g/g}$  for 0.5 wt.% yttrium) and approximately 1300  $\mu\text{g/g}$  of the oxygen now bound in oxides was scavenged from the titanium matrix. Therefore, the real oxygen content, dissolved in the titanium lattice of the yttrium-containing sintered parts is the measured value of 4178  $\mu\text{g/g}$  decreased by 1350  $\mu\text{g/g}$ , bound by the  $\text{Y}_2\text{O}_3$ .

Therefore, the real oxygen content of the titanium lattice of the sintered HDY-parts must be corrected to

2878 µg/g, This value is significantly lower than the critical value of 3200 µg/g where plastic tensile elongation decreases significantly. Therefore, the HD - and the HDY-parts should show completely different behaviours in tensile tests.

As predicted, the sintered HD-parts showed a low ductility and high tensile strength based on the high oxygen content in the titanium lattice, while the HDY-parts showed a higher ductility and lower strength [see Fig. 10 and Table 6].

Due to the scavenging effect, the usage of a mixture of 20% plasma atomised and 80% HDH powder with an addition of 0.5% yttrium powder (HDY) led to a lower yield strength (827 MPa) and ultimate tensile strength (939 MPa) and a higher ductility of 13.5%, based on the lower oxygen content in the titanium lattice compared to the HD-parts. The achieved ductility was only 1 percentage point lower than that of the specimens produced from plasma atomised powder, but coupled with 57 MPa higher ultimate tensile strength.

### Iron as a low-cost sintering aid for Ti-6Al-7Nb processed by MIM

Finally, a paper from Alexandra Amherd Hidalgo, Thomas Ebel and Florian Pyczak, in collaboration with Robert Frykholm (Hoganas AB, Sweden) and Efrain Carreno-Morelli (University of Applied Sciences and Arts, Switzerland), considered the use of iron as a low-cost sintering aid in the MIM processing of Ti-6Al-7Nb [4].

Ti-6Al-7Nb is a promising alloy for load bearing medical applications, on the basis of its corrosion resistance and favourable mechanical properties. Ti-6Al-7Nb alloy has been successfully manufactured by MIM, generating around 700 MPa yield strength and 16% elongation when sintering was performed at 1350°C for 4 h. However, this yield strength is below the minimum required value (800 MPa) indicated for surgical implant applications in

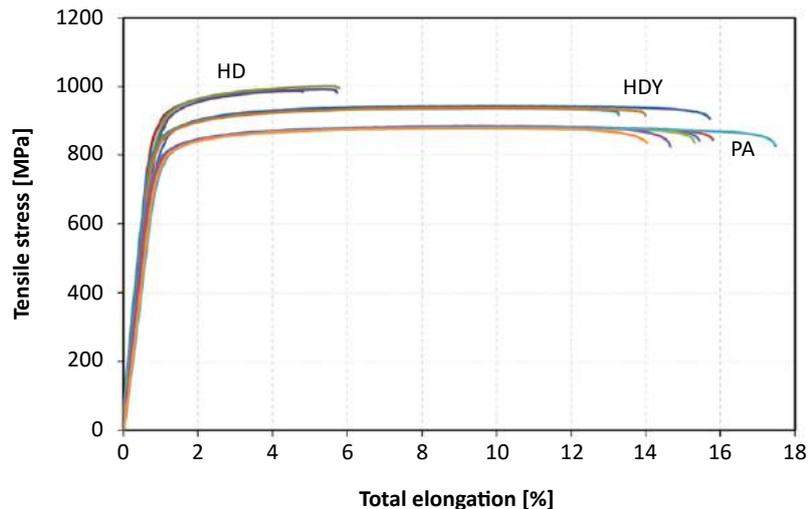


Fig. 10 Tensile test graphs for the various sintered samples [3]

Feedstock	YS [MPa]	UTS [MPa]	$\epsilon_f$ [%]
HD	889 ± 5	994 ± 7	4.5 ± 0.5
HDY	827 ± 8	939 ± 4	13.5 ± 1.1
PA	776 ± 7	882 ± 2	14.6 ± 1.1

Table 6 Tensile test results from the sintered specimens [3]

ASTM standard F1295. Therefore, all possibilities for further enhancement of mechanical performance need to be investigated.

One such option could be the use of sintering aids, because enhanced sintering activity leads to higher densities and, thus, better mechanical properties. In this way, lower sintering temperatures or shorter sintering times might be used and, consequently, production costs reduced. It has been shown that the use of iron accelerates the densification process of PM titanium through the high diffusivity of iron in titanium. However, the iron powder size appears to be an important factor in the densification process. Previously published work has shown that the use of fine iron powders with a D50 of 7 µm enhances densification, while coarser iron powders with a D50 of 88 µm diminish the sinterability of PM titanium due to Kirkendall porosity and an exothermic reaction. Also, the amount of iron is an important factor, as the use of more than 2 wt.% iron reduces the ductility of titanium due to grain growth or the

formation of a TiFe intermetallic phase. Therefore, the combination of using fine iron powder with a technique that avoids grain growth might be promising.

In addition, mechanical properties are influenced by the interstitial content of the titanium alloy. The term oxygen equivalent ( $O_{eq}$ ) can be used to describe the combined influence of oxygen, carbon and nitrogen on the strengthening and embrittlement processes of pure titanium by solid solution hardening:

$$O_{eq} = C_O + 2 C_N + 2/3 C_C$$

where  $C_O$ ,  $C_N$  and  $C_C$  represent the concentrations of oxygen, nitrogen and carbon, respectively.

In the reported work, the use of fine iron powder in combination with a lower sintering temperature (1250°C) was studied in MIM Ti-6Al-7Nb-2Fe. Tensile and high-cycle 4-point bending fatigue tests were carried out and the results were compared with MIM Ti-6Al-7Nb sintered at 1350°C.

Powder	Oxygen [wt.%]	Nitrogen [wt.%]	Carbon [wt.%]
Ti-6Al-7Nb	0.211	0.004	0.007
Iron	0.314	0.005	0.046

Table 7 Interstitial contents of the powders [4]

Alloy	Geometry	% Relative density	Shrinkage [%]
Ti-6Al-7Nb	Tensile	97.1±0.0	12.05±0.03
Ti-6Al-7Nb-2Fe		96.4±0.0	12.13±0.09
Ti-6Al-7Nb	Fatigue	96.8±0.0	12.08±0.11
Ti-6Al-7Nb-2Fe		96.4±0.0	12.08±0.06

Table 8 Relative density and shrinkage of MIM Ti-6Al-7Nb specimens sintered at 1350°C and MIM Ti-6Al-7Nb-2Fe specimens sintered at 1250°C [4]

Alloy	Geometry	Oxygen [wt.%]	Nitrogen [wt.%]	Carbon [wt.%]	O <sub>eq</sub> [wt.%]
Ti-6Al-7Nb	Tensile	0.25±0.01	0.06±0.01	0.04±0.00	0.35±0.03
Ti-6Al-7Nb-2Fe		0.24±0.01	0.07±0.01	0.07±0.00	0.42±0.03
Ti-6Al-7Nb	Fatigue	0.26±0.00	0.01±0.00	0.03±0.00	0.30±0.00
Ti-6Al-7Nb-2Fe		0.25±0.00	0.02±0.00	0.05±0.00	0.32±0.00

Table 9 Interstitial contents and oxygen equivalent contents of tensile specimens [4]

Alloy	Geometry	Colony size [µm]
Ti-6Al-7Nb	Tensile	148±6
Ti-6Al-7Nb-2Fe		84±4
Ti-6Al-7Nb	Fatigue	149±6
Ti-6Al-7Nb-2Fe		82±8

Table 10 Average colony sizes of MIM Ti-6Al-7Nb specimens sintered at 1350°C and MIM Ti-6Al-7Nb-2Fe specimens sintered at 1250°C [4]

The pre-alloyed Ti-6Al-7Nb gas atomised powder used was produced at Helmholtz-Zentrum Geesthacht. The particle size was below 45 µm and the interstitial contents, measured by carrier gas hot extraction, are presented in Table 7. The spherical iron powder used had a particle size distribution with D10 = 3 µm, D50 = 6 µm and d90 = 14 µm and the interstitial contents as presented in Table 7. Pre-mixing of the Ti-6Al-7Nb and 2 wt.% iron powder was performed under argon atmosphere in a planetary mixer for 15 min.

Feedstock was produced by mixing the powders with 10 wt.% of a multicomponent binder, containing 35 wt.% of polyethylene vinyl acetate, 60 wt.% of paraffin wax and 5 wt.% of stearic acid, at a temperature of 120°C for 2 h in a sigma blade mixer under argon atmosphere. Hot extrusion was used to homogenise the feedstock.

Injection moulding was performed on an Arburg 320S Allrounder 500-60 machine. MIM specimens of two different geometries were manufactured; tensile

test specimens (according to ISO 2740) and four-point bending fatigue specimens.

Solvent debinding was then carried out in a hexane bath at 40°C for 15 h and, subsequently, thermal debinding in the sintering furnace below 450°C under 5 mbar of argon flow at a rate of 150 L/h. A subsequent step was performed at 600°C for 1 hr to ensure an adequate removal of binder residuals before sintering. Ti-6Al-7Nb specimens were sintered after thermal debinding in a cold-wall furnace with Mo-shielding and tungsten heater, at a temperature of 1350°C for 4 h under high vacuum using yttria coated molybdenum sintering supports. However, Ti-6Al-7Nb-2Fe specimens were sintered at 1250°C to evaluate the combination of the iron addition and the use of lower sintering temperatures.

Specimens containing iron, sintered at lower temperatures, showed lower densities (Table 8). Shrinkage of specimens followed a similar trend. The interstitial content of specimens is presented in Table 9 and shows an increase in carbon when iron is used. This pick-up of interstitials might occur due to a non-optimised binder removal during the thermal debinding step. The term oxygen equivalent (O<sub>eq</sub>) was used to compare the content of interstitials.

Backscattered electron images present a homogeneous α+β lamellar microstructure with residual porosity. The α phase is presented as dark grey regions and the β phase as light grey regions. The residual pores have a round shape with a maximum pore size of approximately 40 µm. A higher amount of fine porosity is observed when iron is used in combination with lower sintering temperatures. This result is in agreement with the density, measured by the Archimedes method and presented in Table 8. It seems that the use of iron produces an increased amount of β phase and thicker β lamellae are found in the microstructure. In fact, iron stabilises the β phase of

titanium leading to a decrease of the  $\beta$  transus temperature. Thus,  $\alpha$  phase precipitates at lower temperatures and, consequently, has less time to grow and coarsen. In addition, a finer colony size is found when iron is used in combination with lower sintering temperatures (Table 10).

The tensile properties of MIM Ti-6Al-7Nb-2Fe, sintered at 1250°C, are presented in Fig. 11. Results are compared with MIM Ti-6Al-7Nb, sintered at 1350°C. Tensile and yield strengths are approximately 100 MPa higher when iron was used, although the specimens were sintered at lower temperatures and present 0.7% lower densities (Table 8). This result suggests that iron produces a high strengthening behaviour that counteracts the effect of reduced density. In fact, iron enters as a substitutional solid solute in  $\beta$  titanium, hindering dislocation motion and, thus, strengthening occurs. In addition, a higher amount of interstitial contents was measured in specimens with iron (Table 9) and this also contributes to the strengthening by interstitial solid solution. Moreover, the observed finer colony size might increase the strength of the material.

On the other hand, both materials exhibit very similar ductility. Despite the restricted dislocation motion, caused by iron in solid solution, the hindered colony growth contributes to the preservation of ductility at around 16%. Moreover, as the oxygen equivalent content in the specimens (Table 9) is below the critical value 0.46 wt.%, interstitial elements should not modify the ductile behaviour of the material.

The HCF S-N curves, presented in Fig. 12, show no significant change with the use of iron and lower sintering temperatures. All specimens were subjected to shot peening surface treatment and had comparable surface quality. The size, morphology and distribution of pores are important factors for the HCF properties of PM titanium alloys. The typical MIM residual porosity is homogeneous, round and small and this was proved to slightly reduce the HCF properties of Ti-6Al-7Nb. In

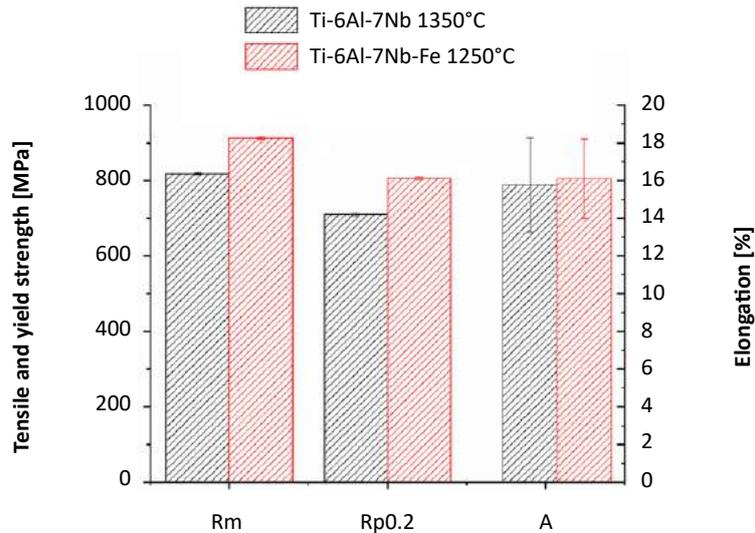


Fig. 11 Influence of iron addition and sintering temperature on tensile properties of MIM Ti-6Al-7Nb [4]

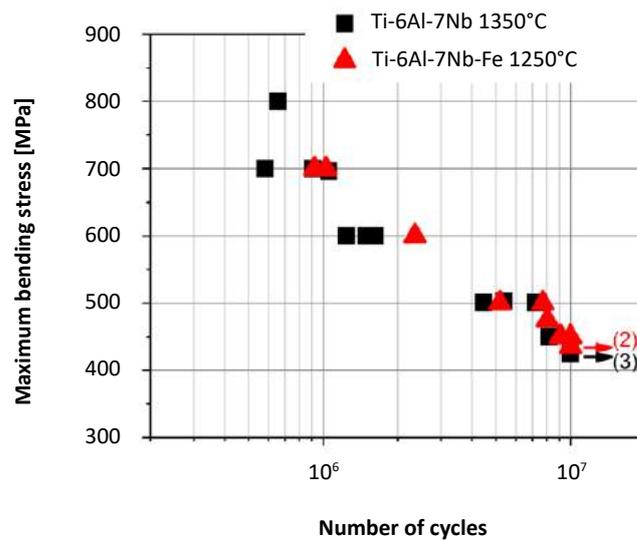


Fig. 12 S-N curves of MIM Ti-6Al-7Nb sintered at 1350°C and MIM Ti-6Al-7Nb-2Fe sintered at 1250°C [4]

addition, the presence of interstitials reduces the HCF behaviour. Fortunately, fine microstructure enhances the HCF behaviour of MIM titanium alloys and the finer colony size achieved by lower sintering temperatures appears to counteract the negative impact of lower density and higher interstitial content when iron is used.

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[2] Improving kinetics of the MIM process by applying new methods of debinding and sintering, Olivier Dugau-guez *et al.* As presented at the Euro PM2018 Congress, Bilbao, Spain, October 14-18, 2018, and published in the proceedings by the European Powder Metallurgy Association (EPMA).

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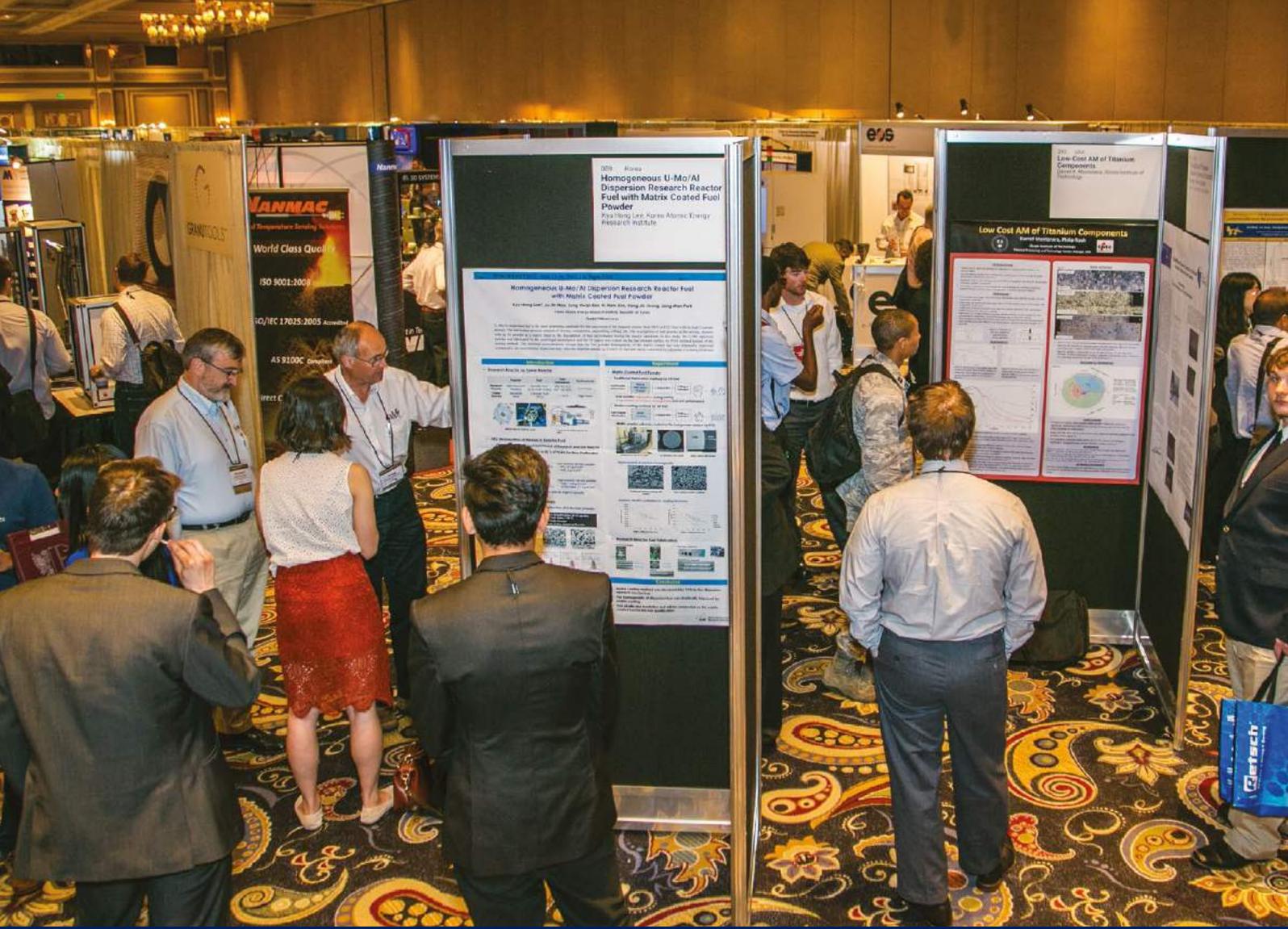
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