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FOR THE METAL, CERAMIC AND CARBIDE INJECTION MOULDING INDUSTRIES

POWDER INJECTION MOULDING INTERNATIONAL

in this issue

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INOVAR COMMUNICATIONS

POWDER INJECTION MOULDING INTERNATIONAL

For the metal, ceramic and carbide injection moulding industries

The next big opportunity

The growth of Powder Injection Moulding is very much tied to the story of a few big applications, with examples of early successes being parts for hard disk drives, airbags, cell phone hinges, dental brackets and watch cases, through to automotive rocker arm components and Apple's Lightning connector.

What all of these applications have in common is that they combine a leverage of PIM's unique capabilities with high volumes and a long production lifespan. Just a handful of such applications have shaped the industry that we have today, particularly in terms of powder, feedstock and processing equipment development.

China today dominates global MIM production thanks to demand for smartphone components, which account for an estimated 66% of the country's MIM output. However, with buttonless phones and wireless charging becoming the norm, this vital market may not last forever.

Conversations at the recent MIM2019 conference in Orlando, Florida, considered the question: Where will industry growth come from next? With the search now on for the next big applications, this issue of *PIM International* considers opportunities for MIM from a materials and technology perspective, as well as presenting solutions that are set to expand the size range of technically and commercially viable PIM components.

Nick Williams,
Managing Director & Editor

Cover image
MIM tungsten heavy alloy prefabricated fragments (Courtesy Jiupeng Song)

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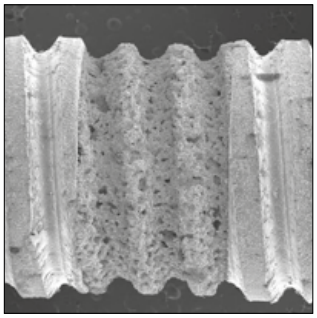

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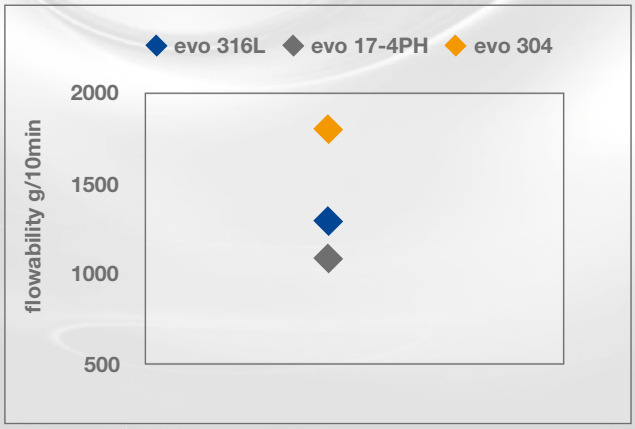

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Industry News

Linden Capital Partners acquires MIM implant specialist Avalign Technologies

Private equity firm Arlington Capital Partners, Washington, DC, USA, has announced the sale of Avalign Technologies, Bannockburn, Illinois, USA, to Linden Capital Partners, based in Chicago, Illinois. Avalign is a provider of proprietary coatings and full-service precision manufacturing solutions, including Metal Injection Moulding, to the orthopaedic medical device and speciality surgical markets. The company is said to offer its partners a broad portfolio of manufacturing solutions and extensive engineering design, development, and project management capabilities.

The company states that its MIM operation is capable of producing relatively large titanium parts with low oxygen levels to meet advanced medical standards. In addition to conventional MIM components, Avalign can produce larger parts including knee femorals, hip stems, shoulder stems, elbow ulnar stems and elbow radial stems.

Matt Altman, a Managing Partner at Arlington Capital, commented, "Our successful partnership with Avalign's founding management team enabled the company to expand its proprietary technology offering, capitalise on strong macro trends in the orthopaedic market and serve as a leading consolidator in the fragmented outsourced medical device manufacturing market."

"The Avalign transaction represents another example of Arlington's thematic approach to investing in the pharmaceutical and medical device industries. We have very much enjoyed the opportunity to partner with the Avalign management team and look forward to watching Avalign's continued success in the future."

Forrest Whittaker, Avalign CEO, stated, "Our partnership with Arlington has been a great success for the company and the management team. Arlington Capital's deep expertise and impressive track record in healthcare and precision manufacturing provided an ideal partnership to help us achieve our goals. Arlington invested significant capital to support our organic growth and to complete several valuable acquisitions which were instrumental to Avalign's growth."

Malcolm Little, a Principal at Arlington Capital, added, "Since our initial investment, Avalign has nearly doubled in size as strong organic growth has been bolstered by several strategic acquisitions. We are proud to have supported the company through this transformation, adding capacity and bringing new technologies into Avalign's portfolio in partnership with the outstanding Avalign management team."

www.avalign.com | www.arlingtoncap.com

CIM provides added value for controllable automotive water pumps

FCT Ingenieurkeramik GmbH (FCTI), Frankenblick, Germany, has replaced a Diamond Like Carbon (DLC) coated steel sliding shoe, used in controllable automotive water pumps, with a new sliding shoe produced from high-performance silicon nitride (Si_3N_4) manufactured by Ceramic Injection Moulding.

Sliding shoes made from Si_3N_4 offer a major advantage in controllable water pumps in that the material enables optimised friction. In motor vehicles, this results in both reduced power consumption and reduced CO_2 emissions.

The task of the sliding shoes is to convert rotary motion into a linear piston movement in an axial piston pump, while simultaneously serving as an active thermal management component for media routing. For this reason, the parts must have high resistance against water, acids, fuels and anti-freezes, must be low weight, and must have high temperature resistance and high dimensional stability, as well as be produced using a reliable and stable manufacturing process. Traceability, quality and flexibility must also be ensured during high-volume production of the sliding shoes, which are used in controllable water pumps for the Volkswagen Group.

In developing the CIM sliding shoes, the partnership between the part developer and customer, Nidec GPM GmbH (NGPM), Auengrund, Germany, and the manufacturer, FCTI, extended to the production of prototype parts, various bench tests and the construction of a first trial mould featuring near-production shapes. This was followed by a further testing programme lasting several months in order to ensure the parts complied with all relevant standards and requirements.

Frank Stegner, Project Manager Automotive at FCTI, stated, "From feedstock development and production, which were carried out using eMBe Products & Service GmbH in Thierhaupten, through to injection moulding, the sintering process and final lapping, we were able to cover the complete manufacturing and machining operation. Arburg then came into play with its injection moulding technology. Ultimately, we obtained the contract largely as a result of this knowledge."

The sliding shoes are produced on Arburg AllRounders equipped for CIM (Courtesy FCT Ingenieurkeramik GmbH)

The new sliding shoes are manufactured in Si_3N_4 using CIM (Courtesy Arburg)

Since September 2017, FCTI has been injection moulding the ceramic sliding blocks on two hydraulic Arburg AllRounder 270 S machines with 4-cavity moulds. On both machines, part removal and set-down in trays is performed by a 6-axis robot. Green compacts shrink by approximately 20% during sintering, which is followed by grinding, lapping and polishing.

Stegner commented that he is highly satisfied with the cooperation between FCTI and Arburg. "We already received excellent advice in the run-up to the machine purchase – from extensive preliminary tests through to customised compound development. Arburg's extensive experience in the field of CIM helped us a great deal."

"The use of the ceramic material has led to reduced friction losses," he added. "This means that both the power consumption and the CO_2 emissions can be sustainably reduced. The power consumption of each water pump has been reduced by approximately two watts. Over two million pumps, this represents an annual saving of some 4,000 kilowatts. Extrapolated to an average annual mileage of 14,000 kilometres per car at an assumed average speed of 50 kilometres per hour and an average driving time of 282 hours, this results in a CO_2 saving of about 983 tonnes."

www.arburg.de | www.fcti.de
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Neota makes new board appointment, targets MIM application development

Metal Injection Moulding specialist Neota Product Solutions, Loveland, Colorado, USA, has recently announced the addition of David Schlosser to its Board of Directors. Jason Osbourne, Neota's President, stated that Schlosser, "brings an impressive background and skillset to the team at Neota and adds valuable resources to our group. We are excited for David to be a key component of our growth plan and our exciting future!"

Schlosser has thirty years of business experience focused on engineering, operations, strategy and change management, finishing his career at EQT Corporation where he was president of the largest natural gas producer in North America and responsible for implementing an annual capital program of $2.5 billion.

Neota is focused on supporting customers from MIM part concept through design for manufacturability, design validation and prototyping into mass production. Through a combination of conventional MIM technologies, rapid tooling and Additive Manufacturing, the company claims that it is able to supply real MIM parts along with custom staging in as little as four weeks.

www.neotagroup.com

Triditive partners with Ecrimesa on debinding and sintering for metal AM

Triditive, Gijón, Spain, a manufacturer of the automated industrial metal Additive Manufacturing system AMCell and founding partner of the Scaladd AM Centre, has announced a strategic partnership with Ecrimesa Group, Santander, Spain, a manufacturer of steel and aluminium parts by MIM and investment casting.

As part of the strategic partnership, Mimecrisa, an Ecrimesa Group company, will support Scaladd in the post-processing of metal parts, providing debinding and sintering services through its three continuous debinding and sintering production lines, as well as two batch production lines with a total production capacity in excess of three-hundred tons per year.

"This collaboration with Ecrimesa will extend the potential market for the MIM industry and will guarantee the possibility to provide the industry our high level of metal production with the highest quality guaranteed by Mimecrisa," stated Mariel Díaz Castro, Triditive CEO. "We look forward to future developments of metallic alloys suitable for AM with the metallurgical laboratory of the Ecrimesa Group."

www.triditive.com | www.grupoecrimesa.com

Hinge makers set on MIM capacity expansion

Taiwan-based *Digitimes* reports that 3C hinge makers are set to expand their Metal Injection Moulding capacity in 2019 to satisfy increasing demand from notebook vendors, according to sources from the upstream supply chain.

Digitimes stated that, after Apple adopted MIM hinges for its MacBook series products, other brand vendors have also begun using similar types of hinges for their devices, significantly boosting demand. In addition to notebooks, MIM hinges have also been used in many other types of 3C products, including the Apple AirPods' charging box. Sources stated that these hinges are supplied by Taiwan-based Shin Zu Shing (SZS) and a US-based maker. SZS had a total of thirty-four batch furnaces and two continuous furnaces for MIM production before installing four more batch furnaces at the end of December 2018. SZS's MIM hinge business currently comprises 10% of the company's overall revenues.

The report also stated that Jarllytec, again based in Taiwan, has increased its MIM furnace capacity and is planning to add two MIM batch furnaces in 2019. In addition to the seven in-house furnaces, it was reported that Jarllytec has another seven externally-contracted batch furnaces to boost its overall output.

www.digitimes.com

Injex collaborates with Parmaco to offer MIM prototypes in days

Injex AG, a small start-up company from the Swiss Federal Institute of Technology Zürich (ETH Zürich), recently exhibited its rapid prototyping and small series injection moulding technology at the Additive Manufacturing Expo in Luzern, Switzerland, March 12-13, 2019. Oliver Schlatter, CEO of Injex AG, stated that the company uses production-grade materials, including metals and ceramics, and a self-developed fully automated, small-format injection moulding machine with clamping force up to 100 kN, to produce prototype and small-series micro parts in the weight range of 0.01 to 20 g in just two to three days.

The company stated at AM Expo that key to reducing lead times to just a few days for producing the prototypes, compared with the twelve weeks or more currently required, is the use of a high-resolution Additive Manufacturing process to produce compact injection mould tooling from the specific CAD file of the component. As well as shortening the lead time to a few working days, the AM tooling allows the prototype MIM parts to be tested quickly and with greatly reduced risk before volume production is started. AM also dramatically reduces the typically-high initial investment in developing an injection moulding tool.

A MIM part manufactured in serial production by Parmaco (left) and the Injex prototype (right)

Injex has been collaborating with Parmaco Metal Injection Moulding AG, a leading European MIM producer based in Fischingen, Switzerland, to further develop Injex's proprietary injection moulding system using the company's MIM feedstock. The green prototype parts are debound and sintered at Parmaco, where any further finishing processes can also be carried out. The dimensional accuracy and mechanical properties of the sintered MIM prototype parts produced using the AM tooling are said to correspond very accurately to the MIM parts in subsequent series production. The technology developed by Injex is also believed to have considerable potential for the economic production of small series – up to 100 pieces – of MIM parts for applications, for example, in the medical sector.

www.injex.ch | www.parmaco.com

AM helps MIM company drastically reduce product lead time

The prototyped parts produced on an Innovent+ Binder Jetting system from ExOne (Courtesy The ExOne Company)

Metal Injection Moulding producer MIMtechnik GmbH, Schmalkalden, Germany, has reported that it is reducing the lead time for prototype MIM products to as little as one week using Binder Jet Additive Manufacturing. The company selected an Innovent+™ Binder Jet AM system produced by The ExOne Company, North Huntington, Pennsylvania, USA, to develop prototype fasteners for building hardware for customer evaluation.

Tooling for MIM is traditionally expensive and the lead time for new moulds is usually from ten to fourteen weeks. The use of Binder Jet Additive Manufacturing reduced lead time for the prototype product to just one week after the initial customer enquiry, while eliminating prototype tooling costs, reported to be typically in the range of €10,000–20,000.

In addition, because the Innovent+ system produces parts using the same 316L high-density single alloy powders as used in its MIM products, MIMtechnik was able to use its current sintering process on the prototyped parts. This meant that the prototype's properties matched what the customer could expect from final MIM parts.

The successful delivery of the prototypes to the customer resulted in an order for approximately 600,000 MIM parts in the first year of production, expected to increase to 1.2 million parts in the following years.

www.exone.com

www.mimtechnik.de

Ceramic Injection Moulding to take centre stage at Ceramics Expo 2019

Ceramics Expo 2019, the fifth edition in the event series organised by Smarter Shows, Brighton, UK, will be held at the I-X Center in Cleveland, Ohio, USA, from April 30–May 1, 2019. The extended uptake of technical ceramics has been a core aim of the Ceramics Expo series of events ever since the inaugural show in 2015, where Ceramic Injection Moulding was identified early on as one of the lead technologies in this field.

During the exhibition, leading exponents of the ceramics industry are expected to showcase many and various engineering components that fall into the domain of CIM. Originally seen as an extremely attractive option for the high-volume production of, especially, smaller items, the technologies underpinning this forming method have evolved such that medium- and low-volume runs (employing low-pressure CIM, for instance) can be managed effectively and can become commercially feasible. There is little waste, it's energy efficient and total production time is optimised.

Where CIM comes into its own is where there is a requirement for complex design, shapes and profiles, and different geometries. In many instances, these demands relate to products that play a significant role in the industries from which Ceramics Expo is said to draw a large proportion of its visitors – healthcare/medical, aerospace, automotive, electrical/electronics, energy storage, defence, and machining.

Ceramics Expo is also expected to attract a number of suppliers of the granulated ceramic feedstock used in CIM, who will showcase their latest work in the field. Further, manufacturers of moulds, sintering furnaces, in-furnace supports (trays and setter plates) and post-process machining will exhibit during the show. Exhibiting companies include 3DCeram Sinto, XJet, Inmatec Technologies, Morgan Advanced Materials, Formatec Ceramics, Saint-Gobain Ceramics, Corning, 3M Advanced Materials Division, Kyocera, CoorsTek and more.

Held concurrently with the exhibition, the Ceramics Expo Conference will also offer insight into current and future developments in technical ceramics and their applications, as well as providing practical advice on cost reduction and the scaling up of central manufacturing processes. Featured sessions on cutting-edge applications for energy storage (day 1) and advances in electro-ceramics (day 2) may be of particular interest to the CIM industry.

Registration for Ceramics Expo 2019 is now open and is free of charge. Further information on the exhibition and conference programme is available via the event website.

www.ceramicsexpousa.com

Demcon acquires SHN International, targets MIM handcuffs market

Lightweight, strong and secure handcuffs are on the wish lists of both national and international security services. Several of the most important components of these handcuffs, reports Demcon, Enschede, the Netherlands, can be produced most effectively using Metal Injection Moulding. Commissioned by SHN International, the Netherlands, Demcon MIM, a subsidiary of Demcon, redesigned an existing lightweight handcuff which enabled SHN to win the contract for a national security service. Demcon MIM now produces various components as well as the entire assembly.

Ritsaert Willemse, SHN International, stated, "The opportunities for MIM largely lie in the combination of serial production, high product complexity, freedom of form and high quality standards. Where required, our products offer a high degree of precision and satisfy high standards with respect to aesthetics, partly because of the material's corrosion resistance. The lightweight handcuff is a fantastic illustration of this."

Demcon MIM was responsible for the partial redesign of the existing SHN handcuff. MIM was selected as production technology for several important handcuff components, explained Rob Egberink, Demcon MIM Managing Director. "This technology enables the manufacture of lightweight and often thin-walled products with complex geometries that satisfy stringent handcuff standards for strength and rigidity." Demcon MIM optimised the design of these components and the associated production process, produced test parts and demonstrated that these satisfy all specifications. The new handcuff is not only reported to be lightweight and thus comfortable to use, but it is also strong and secure.

Lightweight handcuffs with MIM components manufactured by Demcon MIM (Courtesy Demcon MIM)

As SHN is a relatively small business and this is an attractive and large contract, it was recently reported that Demcon would take over SHN. The aim was to safeguard SHN's continuity and growth, stated Dennis Schipper, Director of Demcon. "Being part of our company gives SHN a much greater operational and financial strength in the development, production and marketing of its innovative handcuffs. Moreover, we have a diverse international clientele, which means we are familiar with having to conform to a diverse range of client and market demands." SHN International is continuing under the name Demcon Safety & Security Systems, with Willemse as Business Developer tasked with further exploiting the international market. "Under the wings of the Demcon group, we have an outstanding growth perspective for our handcuff range."

Demcon Safety & Security Systems and Demcon MIM are now exploring the opportunities for growth. Together with a specialist in government purchasing, they are investigating opportunities for the supply of handcuffs to security services in various European countries. "We cannot yet say which countries that will be," stated Egberink. "However, it is the case that each country sets its own requirements for handcuffs, so we will first need to make prototypes for tests and qualification." The semi-civil market is also interesting. Demcon Safety & Security Systems and Demcon MIM are therefore developing 'civil' handcuffs, for instance for special investigating officers and authorised security companies. Authorised personnel can be equipped with these handcuffs.

The production of the MIM parts and the assembly of the handcuffs currently takes place at the Demcon site in Oldenzaal, but will relocate to Enschede this year. As part of its growth strategy, Demcon is opening a new technology centre there with space for 200 employees. The Demcon Technology Centre comprises a Smart Industry Experience Centre, a metrological demonstration and service centre, instrument manufacturing, as well as space for production and clean room assembly. This space is equipped with state-of-the-art facilities for Metal Injection Moulding and assembly and the opening of the Demcon Technology Centre is planned for this summer.

Demcon, with 600 employees, develops, produces and supplies technology and products worldwide for areas such as high-tech systems, medical systems, industrial systems & vision, optomechatronic systems and robotic systems.

www.demcon.nl/demcon-mim

Cobra uses Metal Injection Moulding to create King MIM wedge

A number of golf equipment manufacturers have for a number of years been using Metal Injection Moulding technology to produce tungsten weights which are inserted into golf club heads allowing for greater balance and improved directional control and higher ball speed. Now Cobra Golf of Carlsbad, California, USA, reports that it is using MIM to produce its new King MIM wedge, with the entire head made from 304 stainless steel.

Cobra states that after sintering the MIM wedges undergo a robotic polishing procedure on areas such as the sole and topline. By using robotic polishing instead of hand polishing, the company claims to produce the 'perfect' MIM wedge each time. A circular micro-groove was added to the face of the MIM wedge to maximise spin, almost identical to the design found on the face insert of the Cobra King F9 Speedback driver. The company also opted to chromium plate the MIM 304 stainless wedges to ensure that they last longer for the recreational player.

The new Cobra King MIM wedge made from 304 stainless steel (Courtesy Cobra Golf)

www.cobragolf.com

MIM IGBT parts for EVs under threat

Metal Injection Moulding is used to manufacture heat dissipation components for the IGBT (Insulated Gate Bipolar Transistor) modules of electric vehicles, an application that is seeing dramatic sales growth. It has, however, been reported by *Digitimes*, Taiwan, that metal stamping specialist Jentech Precision Industrial, Taiwan, is supplying its cold water-cooled IGBT modules into the supply chain of a Europe automaker and is planning to win validations for the modules from more first-tier automakers in the US, Japan and Europe in 2019.

The report stated that Jentech has adopted a forging process instead of MIM, achieving better quality parts at a lower cost. The International Energy Agency (IEA) estimated that global sales of electric vehicles will rise to 125 million units by 2030, from 3.1 million in 2017.

www.digitimes.com

EPHJ trade show on high-precision manufacturing to take place in June

The EPHJ-EPMT-SMT trade show (EPHJ) for the high-precision industry is set to run from June 18–21, 2019, at Palexpo in Geneva, Switzerland. The event brings together the main high-precision industries of watchmaking and jewellery, microtechnologies and medical technologies under one roof, and in 2018 saw 800 exhibitors and more than 20,000 visitors in attendance. Both Metal Injection Moulding and metal Additive Manufacturing have key applications in these areas, and will feature in the exhibits and on the programme of presentations.

EPHJ – Professional Watchmaking and Jewellery
Exhibitors from this sector will show their latest products in training, creation, design and CAD; raw materials and components; machines, tools and control devices; microtechnologies; packaging and commercial display; management, marketing, communication and consulting services, and more throughout four days of exhibits and talks.

EPMT – Microtechnology
Exhibitors are expected in the fields of aeronautics and automobiles; automation and robotics; metrology; optics and photonics; laser technologies; logistics and more.

SMT – Swiss Medical Technologies
Companies operating in this sector will present their latest solutions for research and development; the production of materials; machines and equipment; implants, prosthetics, technical parts and components; specialised medical device services and more.

Visitor registration will open at the end of March 2019.

www.ephj.ch

PyroGenesis to partner with Aubert & Duval on titanium powder supply

Aubert & Duval, Paris, France, a subsidiary of Eramet Group's Alloys division which specialises in high-performance metallurgy, and PyroGenesis, Montreal, Canada, a provider of plasma atomised spherical metallic powders for the MIM and Additive Manufacturing industries, have entered into a partnership agreement for the supply of titanium powders in Europe.

To extend its current portfolio of metal powders for the AM market, Aubert & Duval will partner with PyroGenesis to manufacture and distribute plasma atomised titanium powder, allowing the company to ensure the exclusive distribution of these powders in Europe, its primary market. Under this agreement, the new titanium offering from Aubert & Duval will be marketed under the Pearl® Micro brand.

Eramet Group's Alloys division reported that it expects the partnership to allow Eramet to reach a 15% market share of titanium powders in Europe by 2022. The group presently produces superalloy metal powders, notably for aircraft engines and land turbines in the energy sector, as well as stainless steel powders for various markets including automotive.

Jérôme Fabre, Eramet Group's Deputy CEO in charge of the Alloys division, commented, "With our metallurgical expertise for demanding markets such as aeronautics and energy, this partnership with PyroGenesis allows us to complete our offer of metal powders for Additive Manufacturing, including 3D printing, a growing market of the industry of the future."

www.aubertduval.com
www.pyrogenesis.com

MPIF Digital Library contains thousands of PM and PIM manuscripts

The Metal Powder Industries Federation (MPIF) has announced the launch of the MPIF Digital Library, an online database reported to contain thousands of technical manuscripts from MPIF technical conferences.

Manuscripts dating as far back as 1946 can be bought and downloaded individually, rather than requiring the purchase of the entire proceedings.

The MPIF Digital Library includes a fully searchable listing of abstracts, with the option to search by title, author, keyword, publication type, category, keyword, or year. Discounted rates are available for MPIF and APMI members.

www.mpiflibrary.org

MIM2019 conference reflects the convergence of MIM and 'MIM-like' AM technologies

MIM2019, the International Conference on Injection Molding of Metals, Ceramics and Carbides, took place in Orlando, Florida, USA, from February 25-27. Organised by the Metal Injection Molding Association (MIMA), an association of the Metal Powder Industries Federation (MPIF), this year's conference attracted just over 150 attendees, representing ninety-five companies from fifteen countries. The event once again saw a significant number of delegates from the metal Additive Manufacturing industry, in particular those with a focus on the 'MIM-like' Binder Jetting and Fused Filament Fabrication processes.

In addition to technical sessions comprising more than twenty presentations, twenty-eight companies showcased their products and services during a tabletop exhibit. Twenty-three of these exhibitors provided short commercial presentations for their companies intermittently throughout the first day of the conference.

Immediately prior to the MIM2019 conference, a Powder Injection Molding Tutorial was presented by Prof Randall German, Professor Emeritus of San Diego State University, that attracted nearly fifty students. The annual PIM Tutorial gives an opportunity for individuals who are looking for a solid grounding in PIM technology to obtain a comprehensive foundation in a short period of time.

The conference started with a keynote presentation by Robert Dowding, U.S. Army Research Laboratory. The presentation, Development of Particulate Materials and Their Processing for Army and Defense Applications, discussed the U.S. Army Research Laboratory's engagement in the research of materials across all disciplines with the development of metallic compositions as an area of emphasis. The purposes and applications of these alloys ranging from ballistic protection of vehicles and personnel, armament and projectiles, aviation propulsion, to Additive Manufacturing in advanced locations were discussed. The presentation also covered the synthesis of materials including Fe-Ni-Zr, Cu-Ta, and Ni-based alloys with highly stabilised nanocrystalline grain structure, and the fabrication of parts and components from them. High-energy ball milling and other synthesis methods were also discussed, as well as field-assisted sintering technology and Hot Isostatic Pressing. The ARL Open Campus concept for working with and in the U.S. Army Research Laboratory was also presented.

For the third year in a row, MIMA provided seven students with a grant to attend the conference, make a technical presentation and network with professionals in the field. This year's grant-winning students were:

- Jacob Biddlecom, Clemson University, United States
- Santiago Cano Cano, Montanuniversitat Leoben, Austria
- Nicholas Labodycz, University of Massachusetts, United States
- Monica Martinez, University of Louisville, United States
- Lingbin Meng, Indiana University, Purdue, United States
- Juan Alfonso Naranjo Simarro, UCLM PIM Research Lab, Spain
- Jian Zhang, Indiana University, Purdue, United States

The next event in this series takes place from March 2-4, 2020, in Irvine, California, USA.

www.MIM2020.org

New metal Additive Manufacturing system based on MIM technology

Qingdao Greenlong Machinery Equipment Co., Ltd., based in Qingdao, China, has developed its first Additive Manufacturing system based on Metal Injection Moulding (MIM) technology. According to the company, the system, titled the P/FFDM 3D Printer, which can be used to build parts in metal, ceramic or plastic, has achieved successful results for the AM of large parts, with most test parts weighing more than 300 g and the largest part said to weigh over 5000 g.

Greenlong developed the machine with the aim of solving a key pain point of MIM – the long lead-times involved in the development and production of tooling for each new product. The machine was developed using plastic Fused Deposition Modelling (FDM) technology as its basis, while drawing on Greenlong's experience as a maker and user of injection moulding machines.

By using the P/FFDM for the production of MIM tooling, companies which use MIM can significantly reduce product lead times. Further, the machine uses standard MIM feedstock and produces parts requiring debinding and sintering using the same equipment as MIM parts, making it relatively simple for MIM operations to incorporate the new system into their workflow. Greenlong additionally stated that if a product produced on the P/FFDM is found to be wrong or defective, it can simply be broken and reformed into feedstock for a future build.

The company added that the production of components on the P/FFDM machine remains quite slow in comparison to MIM manufacturing and can be an inefficient production method for large volumes of parts. However, it was reported that a new machine is now in the 'debugging stage' which will have the capability to produce parts at speeds comparable to MIM. The new machine is set for release in mid-2019. ■

Greenlong's P/FFDM 3D Printer, a metal AM system based on MIM technology (Courtesy Qingdao Greenlong Machinery Equipment)

EU funding for AddiFab's metal and Ceramic Injection Moulding technology

AddiFab ApS, Jylinge, Denmark, has been awarded an EU grant of €1.6 million to boost the commercial readiness of its Freeform Injection Molding™ technology for ceramic and Metal Injection Moulding. The grant is provided under the SME Instrument, part of the European Innovation Council pilot, with funding from the European Union's Horizon 2020 Research and Innovation programme (grant agreement No 849119).

Freeform Injection Molding is said to combine the short lead-times, low start-up costs and design freedom of Additive Manufacturing with the scalability and use of existing, lower-cost materials offered by injection moulding. It is based on AddiFab's patent-pending Sacrificial Thermoplastic Injection Molding (STIM) technology, which reportedly allows the production of complex injection moulded components in as little as twenty-four hours.

STIM was used for the first time ever for MIM and CIM in 3DIMS, a project funded by the Danish Innovationsfonden. Same-week delivery of CIM samples was achieved, and a number of metal alloys were processed. The project, which involved the Technical University of Denmark and two Danish companies, also led to the identification of improvement opportunities on usability and scalability expected to make STIM more commercially attractive.

In the STIM-MC (Sacrificial Thermoplastic Injection Moulding-Metal & Ceramic) project, AddiFab aims to implement the improvements identified in the 3DIMS project. Furthermore, the company stated that it aims to demonstrate the commercial readiness of STIM for MIM and CIM through test cases with a number of strategic partners.

Ceramic parts produced using AddiFab's Freeform Injection Moulding technology, with sacrificial thermoplastic mould (Courtesy AddiFab ApS)

AddiFab further announced that Uffe Ditlev Bihlet, PhD, former Specialist and Team Leader at the Materials Business Unit of Force Technology, will be joining the AddiFab team. Bihlet is expected to bring a range of experience in advanced Powder Metallurgy to the project, along with an extensive network from academia and industry.

www.addifab.com

Wittmann Group profiles Italian MIM producer, appoints new CEO

The Wittmann Group, which celebrated the 10th anniversary of the integration of Battenfeld Kunststofftechnik with Wittmann based in Kottingbrun, Austria, in 2018, provides a range of injection moulding machines for plastic and Powder Injection Moulding. The company recently profiled Italian MIM producer, Mimest SpA, in its *Innovations* newsletter (3/18). Mimest was established in Trento in 2005 by four engineers specialising in metallurgy, plastics engineering, mechanics and design, with Matteo Perina acting as Managing Director and Rudj Bardini as Technical Director.

Perina stated that, in the beginning, the company invested in knowledge about the MIM production process, and also the development of special equipment, for example for the optimisation of powder mixing. Injection moulding machines were purchased along with debinding and sintering furnaces. Today, Mimest produces more than a million parts a year from a range of materials, with part weights ranging from a few grams to 300 g. Mimest's equipment includes Wittmann Battenfeld EcoPower 55 injection moulding machines equipped with a special CIM/MIM package.

Bardini stated that the all-electric machine guarantees the highest degree of repeatability, as well as energy savings, in Powder Injection Moulding production. In addition, the sensitivity of the electric machine's clamping unit and ejector is said to help protect the relatively fragile green PIM parts. The removal of the green parts from the mould and separation of the parts from the sprues is carried out by a Wittmann R8.3 robot.

From left to right: Rainer Weingraber, Dr Werner Wittmann, Georg Tinschert

Following primary solvent debinding to remove one of the polymer elements of the binder, secondary debinding and sintering is carried out in TAV vacuum furnaces.

New CEO at Wittmann Battenfeld

As of March this year, Rainer Weingraber has taken over the management of Wittmann Battenfeld in Kottingbrunn. He succeeds the company's long-standing Managing Director and CEO, Georg Tinschert, who retired at the end of March.

www.mimest.com
www.wittmann-group.com

Digitalisation the focus at Arburg's Technology Days 2019

More than 6,000 invited guests from fifty-four nations visited Lossburg for Arburg's Technology Days (Courtesy Arburg GmbH + Co KG)

Visitors were provided with an overview of Arburg's digital solutions (Courtesy Arburg GmbH + Co KG)

Arburg GmbH + Co KG, Lossburg, Germany, hosted its Technology Days 2019 from March 13–16, 2019. This year's event marks twenty years of Arburg Technology Days, with the first having been held in 1999, and this, the latest event in the series, saw more than 6,000 visitors from fifty-four countries in attendance.

Arburg stated that the share of visitors from abroad has increased steadily over the years since the first Technology Days event in 1999. This year's event saw 44% of visitors attending from abroad, with the largest foreign groups coming from North America and China. The majority of European guests came via subsidiaries in France, Switzerland, Italy, the Czech Republic, the Netherlands and Austria.

The main focus in 2019 was the 'Road to Digitalisation', with the company offering guests a comprehensive guide to Arburg's digital production solutions. More than fifty of its machines and turnkey systems were showcased during the event, and expert presentations were given on current trends in manufacturing, as well as a guided tour of the operating factory.

The company presented its current offerings in terms of smart machines, smart production and smart services to aid in workflow digitalisation. A particular focus was the 'arburgXworld' customer portal, which can be used by customers in Germany free of charge with Arburg's Machine Center, Service Center, Shop and Calendar apps. The company's digital services are bundled via this service marketplace in the cloud, and the apps are said to be able to provide a quick overview of the machine fleet, enable easy ordering of spare parts with interactive navigation, and allow the creation of service tickets at any time.

Arburg's digital solutions for its machines were also presented. The machines on display were equipped with an Industrial Internet of Things (IIoT) gateway, said to offer flexibility for the implementation of features such as Arburg Remote Services, the Arburg Turnkey Control Module, arburgXworld and the Arburg host computer system, through which all of the exhibits were networked.

Each Allrounder displayed in the Customer Center contained Arburg's six assistance packages as digital components, which are said to actively support the operator, making it easier to work on the machine in line with the production requirements at hand, from start-up, set-up and optimisation to production and monitoring, up to and including servicing.

In its Efficiency Arena, Arburg demonstrated the virtual maintenance of an injection unit using Augmented Reality goggles and video calls. This will allow complex maintenance work to be carried out safely and for faults to be identified and rectified quickly. Real-time monitoring of the condition of wearing components and predictive maintenance were also presented as useful tools to prevent malfunctions and unplanned downtime.

As well as the 'Road to Digitalisation', presentations given during the Technology Days included talks on Automotive Engineering and the Freeformer. The programme was attended by more than 1,400 participants, whilst over 1,900 guests took guided factory tours.

www.arburg.com

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Ametek SMP appoints Marucci and expands team

Ametek Specialty Metal Products (SMP), a division of Ametek, Inc., has appointed Michael Marucci as its Vice President Sales and Marketing for Powders. The division, which includes Reading Alloys, Hamilton Precision Metals, Superior Tube, Fine Tubes, SMP Eighty Four and SMP Wallingford, manufactures high purity alloy powders and master alloys, as well as precision metal tubes, strip and foil at six manufacturing facilities in the USA and UK, with sales offices across the globe.

Marucci will be responsible for sales and marketing activities related to titanium master alloys, titanium powders and water and gas atomised powders. Prior to joining Ametek, he was Vice President, Commercial and Strategy, at GKN Hoeganaes.

In the US, Ametek also announced the appointment of Regional Sales Managers Ryan Cicciu and Andrew Blankemeier. Cicciu will identify and develop new customers and product applications for the division's tube, strip and powder products, covering the New England region. Blankemeier will cover the North Central region with a focus on the division's powder, tube and strip products for medical and industrial applications.

Marucci has been appointed Ametek SMP's new VP Sales and Marketing for Powders (Photo via LinkedIn)

The company also announced Pierpaolo Pigliacelli as its new Regional Sales Manager, Western Europe. Responsible for sales and business development in France, Italy, Switzerland, Spain and Portugal, Pigliacelli represents the SMP Division across the board.

In China, Michael Zhu has been appointed as Regional Sales Manager for SMP. Working from the AMETEK Shanghai office, Zhu will be responsible for sales and business development across the SMP portfolio throughout China.

www.ametekmetals.com

AP&C plans growth with expansion of Saint-Eustache

Plasma atomised powder specialist AP&C, a GE Additive company, has purchased a 40,000 m^2 plot in Innoparc Albatros, Saint-Eustache, Montreal, Canada, where it has been based since 2016, to support its future growth plans. The firm currently employs around one hundred at the site.

Alain Dupont, AP&C's President and CEO, stated, "We are thrilled to work with the dynamic Ville de Saint-Eustache team! Our firm is currently enjoying rapid growth and we need more space for our projects, along with a good location for drawing fresh talent. Innoparc Albatros meets both of these urgent needs. It is clear that AP&C's future is right here in Québec and, in particular, Saint-Eustache!"

Pierre Charron, Mayor of Saint-Eustache, commented, "We are extremely proud that AP&C, the flagship of its industry, has decided to multiply its activities in Innoparc Albatros, thereby making big contributions to Saint-Eustache's economy."

www.advancedpowders.com
www.ge.com

PM and AM of Titanium Conference seeks abstracts

A call for papers has been issued by PMTi 2019, the 5th Powder Metallurgy and Additive Manufacturing of Titanium Conference, set to run from September 24–27, 2019, at the University of Utah, Salt Lake City, Utah, USA.

This year's event, sponsored by the Metal Powder Industries Federation (MPIF), will welcome global experts on the PM and AM of titanium and titanium alloys for a technical programme covering a wide range of relevant topics. This conference has previously been held in Australia, New Zealand, Germany and China.

Prof Zhigang Zak Fang, FAPMI, University of Utah, is serving as the Chair of PMTi, alongside Co-chairs Dr Ali Yousefiani, Boeing, Dr James Sears, Carpenter Technology Corporation and Prof H Sam Froes, University of Idaho (retired).

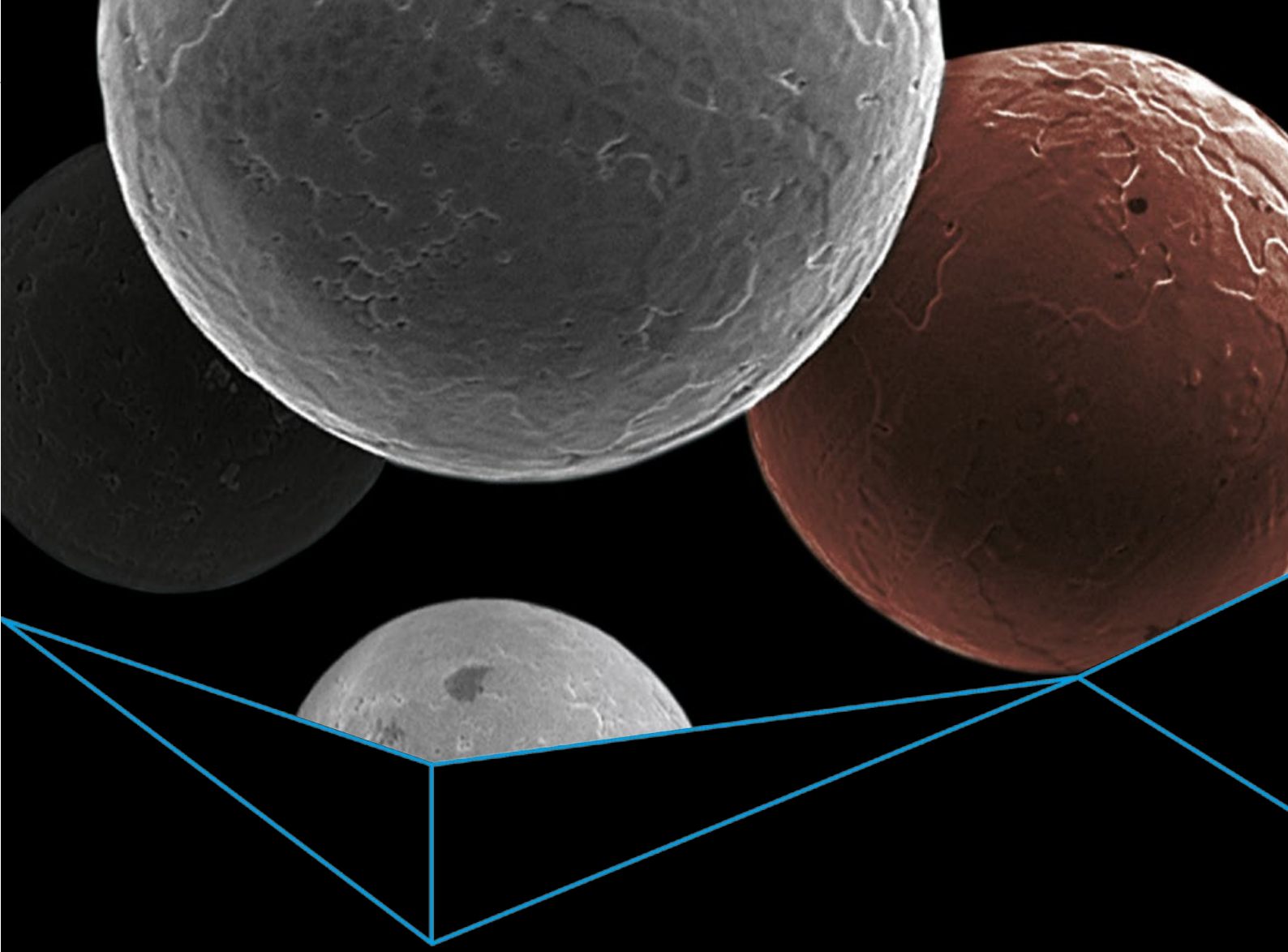
Abstracts should be submitted via the conference website no later than April 15, 2019.

www.tipmam2017.org

Moulding simulation event moves to Shanghai

CoreTec Systems Co Ltd, headquartered in Chupei City, Taiwan, reports that the Moldex 3D Technology Conference (MTC) will be held in Shanghai, China, June 18-19, 2019. MTC will again focus on presenting the latest technology advancements and innovative simulation methods used by the injection moulding sector.

www.moldex3d.com/en/events/conference/mtc-2019/



POWDERMET2019 and AMPM2019: Full conference programmes now available

The Metal Powder Industries Federation (MPIF) has released the full conference programmes for POWDERMET2019: the North American Conference on Powder Metallurgy and Particulate Materials, and AMPM2019: Additive Manufacturing with Powder Metallurgy, set to run concurrently at the Sheraton Grand Hotel in Phoenix, Arizona, USA, from June 23–26, 2019.

POWDERMET2019 will feature more than two-hundred technical presentations from global industry experts presenting on PM and particulate materials. In addition, over one-hundred exhibitors will showcase their technologies and services in the co-located POWDERMET exhibition, and a number of industry networking events such as the 'PM Evening Alehouse' will offer visitors and exhibitors the chance to make contacts within a diverse range of PM fields.

"POWDERMET conferences provide attendees with the opportunity to learn best practices, new solutions and the latest R&D," stated Blaine Stebick, MPIF Technical Board Chairman. "Powder Metallurgy continues to be an innovative technology that inspires the next generation of engineers, especially with the rising influence and interest in metal Additive Manufacturing."

AMPM2019's conference programme will feature worldwide industry experts presenting the latest technology developments in metal Additive Manufacturing. Attendees to AMPM will also have full access to all POWDERMET events including the conference programme, exhibition and networking sessions.

Registration is available at early-bird discounted rates until May 10, 2019.

www.powdermet2019.org

ARC Group reports half year results

ARC Group Worldwide Inc., a global manufacturer of high-precision components by Metal Injection Moulding and precision metal stamping, has reported sales of $41.473 million for the six months to December 30, 2018. This represents an 18% increase in sales compared with the same period in 2017.

The company states that its business model is to accelerate the widespread adoption of MIM, supported by other key technologies including automation, robotics, and production software. In particular, ARC aims to provide a 'one-stop shop' solution to its customers by offering a spectrum of highly advanced products, processes and services, thereby delivering highly-engineered precision components at efficient production yields. ARC operates MIM facilities in the US and Hungary.

www.arcmim.com

3DEO to more than double production capacity for 'MIM-like' process

3DEO, Inc., a Los Angeles-based metal Additive Manufacturing company with a binder-based technology capable of competing with the low-volume MIM market, has reported significant growth in 2018, its second full year of operation. To meet rapidly expanding customer demand, the company plans to more than double its production capabilities in 2019, adding more of its proprietary metal Additive Manufacturing systems.

During 2018, 3DEO manufactured over 30,000 paid parts for customers across a wide variety of industries including medical, aerospace, defence, consumer, and industrial equipment. The company reported that at the start of 2019, it had secured two additional customer production orders for 24,000 pieces and 28,000 pieces, with both orders scheduled for delivery this year.

"We are very proud of what we accomplished in 2018 working hand-in-hand with end-use customers. We are also very excited for what's to come in 2019. By many key manufacturing and customer metrics, 3DEO's technology is setting the standard for serial production metal 3D printing," stated Matt Petros, CEO and co-founder of 3DEO, Inc.

3DEO's patented Intelligent Layering® Technology is said to drastically reduce final part cost, while meeting the high industry benchmark MPIF Standard 35, achieving tight tolerances and an impressive surface finish. The company believes that Intelligent Layering will open metal AM to the industries that can't afford today's expensive options. Leveraging its unique technology as a parts supplier, 3DEO sells high-volume, high-value metal parts to manufacturers with a variety of applications across a wide range of industries.

"3DEO's production metal 3D printing technology is proving itself to be highly scalable and robust. In order to be successful with serial production, part-to-part and machine-to-machine repeatability is paramount. In many ways 3DEO's technology is uniquely capable in the industry of metal Additive Manufacturing," added Marty McGough, COO and head of quality at 3DEO, Inc.

"By all measures, 3DEO is rapidly expanding to fill a large void in the market of small complex metal parts. Customers are validating our technology across a variety of industries and we are either in production or quickly moving to production with many clients. Additive Manufacturing is finally competing directly with traditional manufacturing, enabling significant volumes to shift over to AM. It is a very exciting time for 3DEO, metal Additive Manufacturing and our customers," concluded Petros.

www.3deo.co

Safran research centre to investigate advanced turbine blades

Safran S.A., Paris, France, has opened its new research centre for advanced turbine blades used in airplane and helicopter engines at its plant in Gennevilliers, near Paris. The ceremony was attended by Florence Parly, French Minister of the Armed Forces; Ursula von der Leyen, German Minister of Defence; and Philippe Petitcolin, CEO of Safran.

The research facility is part of the corporate Research & Technology Center, Safran Tech. Housed in a 3,000 m^2 (32,400 ft^2) building, the new research unit is staffed by about thirty engineers and doctoral candidates and is fitted with state-of-the-art machinery and equipment for the development of next-generation, very high-performance turbine blades. The new unit will reportedly deploy Safran's proven expertise alongside innovative technologies such as multidisciplinary design, single-crystal casting, ceramic cores, thermal coatings, cooling circuits, digitised processes, self-adapting micro-drilling and non-destructive testing based on artificial intelligence. The company is also active in the development of Metal Injection Moulding for aerospace applications.

The turbine blades developed at the centre will reportedly be incorporated on the Rafael's current engines to improve aircraft dispatch reliability and reduce through-life maintenance and production costs. The technologies developed by this centre will also be used on the future high-performance engine from Safran Aircraft Engines, the French-German Future Combat Air System (FCAS). In addition, the centre will develop technologies for use on civil aircraft engines and helicopter engines.

Safran's new research centre

During the inauguration, Florence Parly and Philippe Petitcolin signed the renewal of the SME Action support agreement, witnessed by three SMEs: Outillage, Chesneau and MSC Scanning, all suppliers to the research centre. Gennevilliers is one of Safran's 'legacy sites', having been in operation for 110 years. Located about 15 km northwest of Paris, it provides forging, casting and machining services for engine parts from Safran Aircraft Engines, and is organised into three centres of excellence: turbine blades, compressor blades and rotating parts

www.safran-group.com

Elnik announces leadership change and new appointments amid growing demand for MIM-based technologies

Elnik Systems, LLC, Cedar Grove, New Jersey, USA, has announced a number of leadership changes. Effective March 31, Stefan Joens will become President of Elnik Systems, succeeded by Bruce Dionne, who joins Elnik as Vice President of Operations on April 1, 2019. Additionally, Bryan C Sherman joined DSH Technologies, a sister company of Elnik Systems, in January 2019 as Chief Metallurgist and Project Manager.

Stefan Joens takes the helm as President of Elnik ten years after his return to the business, which is owned and operated by himself and his family. He has served on the board of directors of the Metal Injection Molding Association (MIMA) for more than three years, representing the association on the Industry Development Board of the Metal Powder Industries Federation (MPIF), serving as co-chairman of the annual MIM conference and having involvement in other board-directed chairman roles. Claus Joens, his father, will now take over the role of Chairman of the Board and continue to be involved with the organisation.

Elnik stated that its success comes from four core principles: innovation, quality, experience and excellence. "Throughout his working career, Stefan has always kept these at the centre of decision making and helping the company plan for its future," stated Claus Joens. Together with Elnik and DSH Technologies' team of experts, it was further stated that Stefan Joens will have the resources available to carry out his vision of providing a high level of education, practical solutions and essential 'workhorse-style' equipment to metal part making industries.

Bruce Dionne

Bruce Dionne brings to Elnik strong experience in Metal Injection Moulding. He joined the MIM industry in 2006 with Megamet Solid Metals, where he later served as Vice President & General Manager, growing the business to become one of the most respected and fastest growing contract MIM parts providers in the industry. In 2015, Megamet Solid Metals was sold to Ruger Firearms, where Dionne later served as the Director of Operations, growing and improving operations utilising lean manufacturing principals.

Dionne also has ten years of engineering and service-related experience working for Nooter Corporation, at the time one of the leading ASME Section VIII pressure vessel manufacturers in the country, and is expected to provide a unique set of skills and experiences that will work together to meet the new challenges at Elnik. "We are excited to have Bruce join our team," stated the company. "Bruce's real-world growth-oriented operational experiences will help Elnik continue to lead the debind and sinter equipment industry and assist with positioning our organisation to support the new demands coming."

Dionne served for four years as the President of MIMA, as well as serving multiple terms on the MIMA board of directors, four years on the MPIF's Board of Governors and three times as the Co-chairman of the annual MIM Conference.

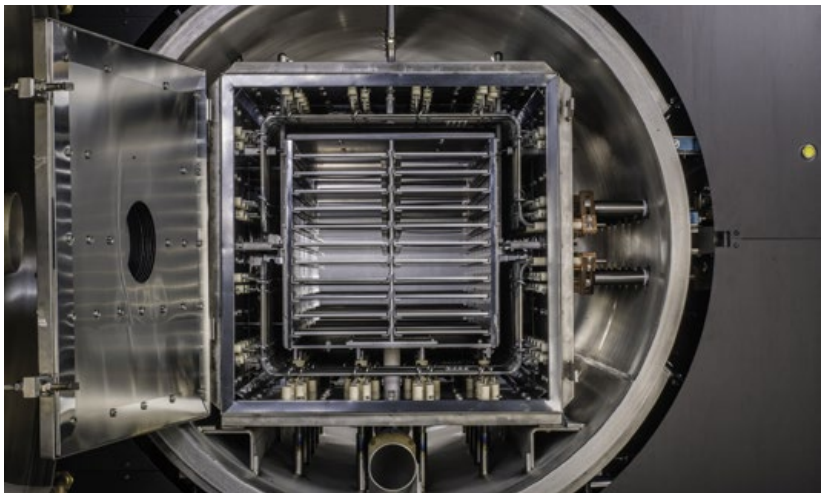
Bryan Sherman

Bryan Sherman comes to DSH Technologies with more than twenty years of experience in the MIM industry. Having been involved with part design, fabrication, equipment design and use, research and development projects and facility management and layout, Sherman brings many years of knowledge to the company.

After completing his BASc in Material Science and Ceramic Engineering at Pennsylvania State University, Sherman progressed from a process engineer to managing sintering and complete process technology at a variety of MIM parts manufacturers. Having worked at the largest captive MIM parts maker on the US East Coast, he will bring real-world experience and solutions-based problem-solving skills as he transitions into his new role at DSH.

"DSH Technologies continues to be the leading partner for the MIM industry, supporting all aspects of process-related improvement throughout the entire supply chain. Bryan's real-world experience will also be of great support and help to the metal Additive Manufacturing industry, which requires knowledge and solutions as it relates to debinding, sintering and process improvements," Elnik stated. "We are excited to have Bryan join our team and help continue to push the high level of education DSH Technologies is positioned to provide to various metal part making industries."

www.elnik.com | www.dshtech.com



Interior view of the molybdenum hot zone in an Elnik MIM 3045 furnace

Eisenmann showcases new One Solution sintering furnace

Eisenmann SE, Böblingen, Germany, recently showcased its new One Solution high-temperature roller-hearth furnace at a special event at its facility in Bovenden, Germany. A number of guests from the Powder Metallurgy and sintering industries viewed the complete system, which included a return conveyer, in the company's preassembly hall at Bovenden.

The One Solution furnace allows the roller-drive speed to be seamlessly and precisely adjusted to the specific needs of the product, and companies operating this furnace are said to be able to achieve substantially lower energy and industrial gas consumption. It also offers all the advantages of high-temperature sintering with rapid cooling and exact management of the atmosphere, while delivering theoretically ideal sintering conditions of 1,400°C in conjunction with cooling rates of up to 8 K/s.

During the event, Peter Vervoort, Eisenmann's Vice President, Product Development & Technology, spoke about the European Powder Metallurgy Association (EPMA)'s 'Vision 2025', a publication designed to serve as a roadmap for the future of the PM industry. Martin Creutziger, Eisenmann's Head of Test Center, provided visitors with an overview of the potential, security and technological possibilities of 'future-oriented' sintering technology.

The One Solution high-temperature sintering furnace in Bovenden, Germany (Courtesy Eisenmann SE)

Vervoort and Creutziger presented the key components and features of the new furnace and explained some of the ways in which Eisenmann has addressed the market need for highly efficient and flexible production. The One Solution high-temperature roller hearth sintering furnace range was said to offer outstanding advantages in terms of product quality, flexibility and operating costs.

Eisenmann SE employs a workforce of over 3,000 staff worldwide, operating at twenty-seven sites in fifteen countries across Europe, the Americas and the BRIC nations (Brazil, Russia, India and China). In 2017, the company reported annual revenues of €723 million.

www.eisenmann.com

Maxon Motor opens new Innovation Centre in Switzerland

After two years of construction, Maxon Motor recently opened its new Innovation Centre at the company's headquarters in Sachseln, Switzerland. The company states that the new six-storey building will provide an environment for the focused collaboration of various research and development departments, and will also offer space for the significantly expanded production of microdrives used in medical technology. These drives are used in insulin pumps, medication delivery systems, or surgical robots. The new Innovation Centre is the fifth building on the Sachseln site which now employs more than 1,200 people.

Maxon Motor has six production sites worldwide, including its own facility for Metal Injection Moulding and Ceramic Injection Moulding in Sexau, Germany. Some of the CIM parts are used in medical microdrives such as gearheads, shafts and bearings to increase performance and to increase life. The CIM parts are non-corrosive and are biocompatible, thereby avoiding allergic reactions.

www.maxonmotor.com

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New ceramitec conference scheduled for September includes PM and PIM

Messe München has announced the launch of the ceramitec conference, a new event in the ceramitec series, to be held at Messe München, Munich, Germany, September 19–20, 2019. The focus of the conference will be on the industrial use of ceramic materials and will include sessions covering Powder Metallurgy, Powder Injection Moulding and Additive Manufacturing.

In a programme set up in a 'matrix format', the ceramitec conference will lay out the industry segments known from the ceramitec trade show – Technical Ceramics, Additive Manufacturing, Powder Metallurgy, Raw Materials and Refractory Materials – over their end-user industries. This, state the organisers, will give attendees the possibility of compiling their own individual programme specifically tailored to their requirements. As a result, it is stated that the event facilitates access to the ceramic industry for new fields of application.

ceramitec is an international ceramics trade fair held every three years in Munich, with the most recent exhibition taking place in April 2018 attended by 15,000 visitors. By creating the ceramitec conference, the organisers aim to shorten the time between the trade fairs.

Today, the ceramic industry is highly innovative due to new manufacturing processes and changed raw material qualities. According to the organisers, shorter innovation cycles make ceramics increasingly attractive for a great number of industrial uses in the automotive and chemical industries, electrical engineering, the health sector, biotechnology, aerospace, mechanical engineering, the pharmaceutical industry, and in the world of design.

Dates announced for the ceramitec 2021 exhibition

Messe München also announced that the next ceramitec trade exhibition, ceramitec 2021, will take place in Munich from May 18–21, 2021. The trade show is held once every three years. ceramitec 2018 attracted 633 exhibitors from 38 countries, including suppliers and producers of Powder Injection Moulding equipment, materials and finished components. The organisers stated that digitalisation and new manufacturing processes are playing an ever more important role at the event, with the 2018 show the first to include a separate lecture programme on Additive Manufacturing. It is expected that the 2021 event will continue to expand this focus.

www.ceramitec.com/conference
www.ceramitec.com

Atect Full-Mould binders

atect

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

- Just regrind the sprue, runner and unwanted green parts then reuse!
- Use 100% reground material without the need for fresh feedstock!
- No change in the shrinkage ratio or physical properties!
- No change in mouldability!
- No need to modify debinding and sintering setup!

Binder system design

Characteristics required for Binder

- **High flowability at molding temperature**
  Binder design considering the viscosity at around the molding temperature.

- **High expansion property in the mold during injection moulding**
  Wide moulding condition range because of the Barus Effect. (Fig.1 and 2)

- **High thermal decomposition property in the de-binding process**
  There is no effect on the sinter quality, because there is no residue after de-binding. (Fig.3)

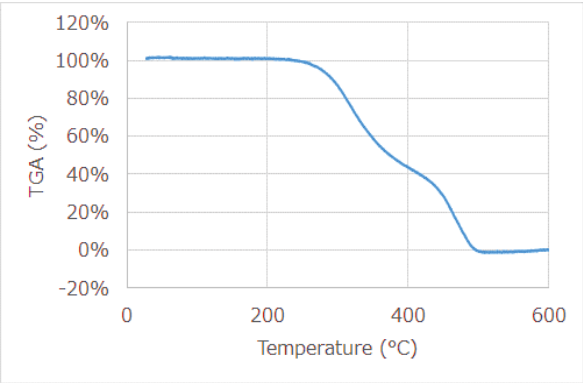

Fig.3 TGA Curve of Binder

※All components are vaporized at around 500℃.

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

$$F = aS^n$$

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

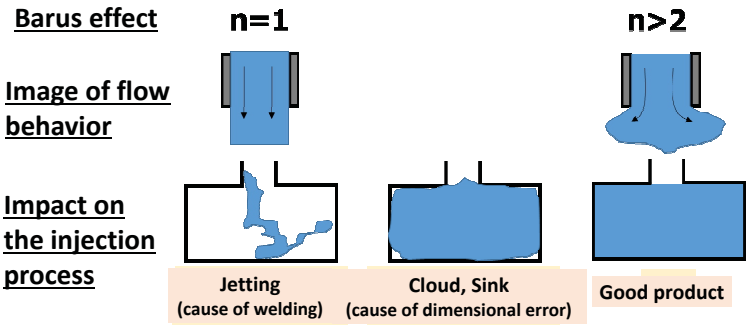

Fig.1 Schematic of the relationship between n value and flow characteristic

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

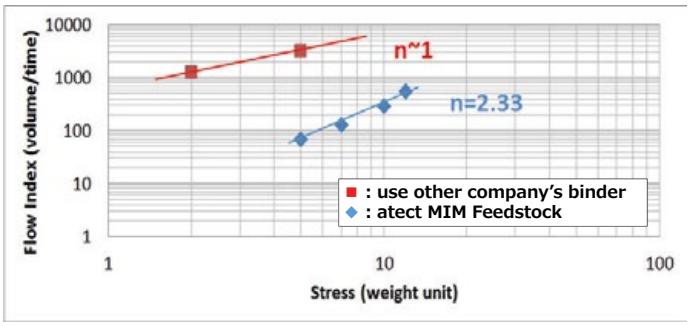

Fig.2 Flow characteristic compared with pellets using the other company's binder

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

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Innovation Center Additive Manufacturing opened at Fraunhofer IFAM Dresden

Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM), Dresden, Germany, has opened its new Innovation Center Additive Manufacturing (ICAM). Based in Dresden, the research institute is combining various technologies for Additive Manufacturing in a newly-constructed technology hall in order to be able to demonstrate to partners and users the wide range of possibilities for the AM of components.

The ICAM houses several systems for Electron Beam Powder Bed Fusion (EB-PBF), including the Q20plus from Arcam EBM, Mölndal, Sweden. This system is said to have the largest build chamber currently available for EB-PBF. In addition, the facility is set to install an Additive Manufacturing Complete and Compact (AMCC) line in the coming weeks. The AMCC line is a prototype production line for the AM of components by Fused Filament Fabrication (FFF), developed by project partner Xerion, Berlin, Germany. While this process is known for the generative manufacturing of plastic components, Fraunhofer IFAM is now expanding its range of materials to include metallic components that were previously not possible.

Fraunhofer IFAM also has several systems available for the three-dimensional screen printing of components. In this technology, based on conventional industrial screen printing, a paste of metal powder is printed layer on layer and is said to offer high precision and have the potential for mass production. The materials fit for the process can reportedly be freely selected and, if necessary, combined in the area of metallic and ceramic materials.

The centre also has equipment for three-dimensional stencil printing where, in contrast to the screen printing method, structured metal foils are used instead of the printing screen to generate components. The institute stated that advantages of stencil printing, compared to screen printing, are the potential for improved surface quality and increased layer thickness.

With the opening of its ICAM, the institute offers partners from industry and research a wide range of services in the form of feasibility studies, the evaluation of powders and the qualification of new materials. Furthermore, it can offer assistance with component development, starting with the powder and continuing through design to production and post-processing. Together with the Fraunhofer IFAM Bremen site, which also has metal Binder Jetting and Laser Powder Bed Fusion (L-PBF) technology, as well as Metal Injection Moulding, Fraunhofer IFAM believes that it now has one of the most comprehensive ranges of technologies for the additive manufacturing of metals.

www.ifam.fraunhofer.de

Elnik to provide MIM expertise to Scaladd Consortium

Triditive, Spain, has announced that US-based Metal Injection Moulding equipment specialist Elnik Systems is to provide comprehensive metallurgical assistance and production services, at its German and US facilities, to the Scaladd Consortium.

The Scaladd Consortium was established by Triditive to grant industrial companies access to Additive Manufacturing production in metals and polymers, as well as the technology and services provided by consortium members. Through the cooperation, Elnik will draw on its expertise in the MIM debind and sinter industry, giving access to its wide range of advanced furnaces suited to the processing of metal components, such as those manufactured on Triditive's AMCell machines. Elnik builds furnaces that can process any metal with any binder, including one-step systems, catalytic and solvent debinding options.

Triditive expressed its hope that the equipment provided will help to make metal AM a 'final solution' for the industry. "We have a clear objective working with Elnik Systems: to demonstrate that AM is ready for mass manufacturing in metals using AMCell® automated machines," stated Mariel Díaz Castro, Triditive CEO.

www.triditive.com | www.elnik.com

EPMA appoints MIM expert Bruno Vicenzi as new Technical Manager

The European Powder Metallurgy Association (EPMA) has announced that Bruno Vicenzi has been appointed as the association's new Technical Manager. The move follows the announcement last year that Dr Olivier Coube was stepping down as EPMA Technical Director in February 2019.

Vicenzi received a Master's Degree in Physics from the University of Genova in 1988, and a Diploma in Material Science and Technology in 1993. He worked from 1990 to 2002 as a researcher in Powder Technology, Materials and Applications at Centro Sviluppo Materiali SpA in Genova. Vicenzi was a founding partner of the Metal Injection Moulding producer MIMI-TALIA Srl, which became Clayver Srl in 2016, and worked there from 2002 to 2019 as a Production Manager, responsible for research projects and liaison with EPMA and the EU. He was also Co-Chairman of the EuroMIM group from 2003 to 2017, and a member of the EPMA Council from 2005 to 2017. Vicenzi will be based out of the EPMA's new office in Chantilly, France.

In his role as Technical Manager, Vicenzi will be actively working with the association's sectoral groups, as well as gathering and analysing relevant industry statistics, organising research projects and working on the development of new research programmes. He will also be responsible for coordinating the EPMA's training and education activities.

Those wishing to contact Vicenzi should email bv@epma.com

www.epma.com

Ruger reports small decline in firearm sales in 2018

Sturm, Ruger & Company, Southport, Connecticut, USA, has reported a 5% reduction in net sales for 2018 at $495.6 million compared with $522.3 million in 2017. The decrease is said to reflect a reduction in overall demand for firearms as evidenced by the National Instant Criminal Background Check System (NICS) and adjusted by the National Shooting Sports Foundation.

The company, whose main market is the production of firearms to the domestic consumer, operates two main segments – firearms and castings. The castings segment includes investment casting of steels and the production of MIM parts. The firearms sector is the biggest consumer of MIM parts in the USA, taking 34% of MIM production in 2017.

www.ruger.com

APMI International names 2019 Fellow Award recipients

APMI International has named Joseph Tunick Strauss and John L Johnson as the recipients of its Fellow Award 2019. Established in 1998, the award recognises APMI members for significant contributions to the goals, purpose and mission of the organisation, as well as for a high level of expertise in the technology, practice or business of the industry.

Joseph Tunick Strauss

Joseph Tunick Strauss, Engineer, President, HJE Company, Inc, has worked to advance the PM and MIM industries through engineering and ingenuity for over thirty years. He was the first to commercially offer turn-key small-scale high-performance gas atomisers and publish on the use of elevated temperature gas for atomisation.

Strauss formally introduced PM to the jewellery industry, and continues to develop press & sinter and Metal Injection Moulding technologies for this market. He has been influential in uniting the PM and Additive Manufacturing communities, and assisted in the formation of the MPIF's AMPM conference. Strauss has served on the APMI Board of Directors and has been on the MPIF Conference Committee for a number of years. He has received many awards including the MPIF Distinguished Service award in 2013.

John L Johnson

John L Johnson, VP Technology, Elmet Technologies, has dedicated over twenty years to research and development of processes and products for the PM industry. Prior to joining Elmet, Johnson was Director of Powder Sales for Kennametal Firth Sterling. Before moving to sales, he held various R&D positions at ATI Firth Sterling, Kennametal, Alcoa Howmet, AMTellect and Penn State University.

Johnson has authored or co-authored more than one hundred technical papers and, as an editorial committee member, reviewed over two hundred technical articles for various technical journals. Johnson has served on many committees and association boards including the APMI Board of Directors and the MPIF Technical Board.

He has been a co-chairman of the Tungsten, Refractory and Hard Materials Conference and continues to organise numerous Special Interest Programs for the annual POWDERMET conferences. While completing his PhD at The Pennsylvania State University, Johnson was a recipient of the 1993 CPMT/Axel Madsen Conference Grant.

www.apmiinternational.org

PMCC 2019 exhibition to take place in Shenzhen

PMCC Expo 2019, the 2019 Shenzhen International Powder Metallurgy & Cemented Carbide Exhibition, organised by Wise Exhibition, will run from May 8–10, 2019, at the Shenzhen Convention and Exhibition Center in Shenzhen, China. Around 30,000 industrial and academic representatives are expected to attend the exhibition, with 500 companies exhibiting.

This year, in addition to the exhibition, the organising committee of PMCC Expo will hold the Asian Summit on Powder Metallurgy Industry Technology Development. The summit will be held during the exhibition, and will include the presentation of industry reports and discussions on the current and future state of Powder Metallurgy.

www.pmccexpo.com

EPMA PM Thesis Competition 2019 now open for submissions

The European Powder Metallurgy Association has launched its 2019 Powder Metallurgy Thesis Competition, sponsored by Högänas AB, and is now 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 must be classified under the topic of Powder Metallurgy (which includes Metal Injection Moulding and metal Additive Manufacturing) and will be judged by an international panel of experts drawn from both academia and industry.

The aim of the competition is to develop interest in and promote PM among young scientists at European academic institutions and to encourage research at undergraduate and postgraduate levels.

The PM Thesis competition winners will be awarded prizes of €750 and €1,000 for Masters and Doctorate levels respectively. In addition, each will receive complimentary registration to the Euro PM2019 Congress & Exhibition as well as the opportunity of having their work published in the scientific journal *Powder Metallurgy*.

www.thesiscompetition.epma.com

Submitting news...

To submit news to *PIM International* please contact Nick Williams: nick@inovar-communications.com

Hannover Messe attracts increasing number of PIM exhibitors

An anticipated 6,500 companies and research organisations from seventy-five nations will be exhibiting at the Hannover Messe – the world's leading trade fair for industrial technology, scheduled to take place in Hannover, Germany, from April 1-5, 2019.

Global corporations, small- and medium-sized enterprises and start-ups alike will all be showcasing their components and system solutions for tomorrow's industrial production and energy systems, with one of the main focuses at this year's Hannover Messe being 'Lightweighting Technologies'.

Powder Injection Moulding is one technology that meets these challenges and it should, therefore, come as no surprise that an increasing number of companies involved in PIM component production have decided to exhibit at the 2019 Hannover Messe. Exhibitors involved in Ceramic Injection Moulding include: Sembach Technical Ceramics, Rauschert GmbH, Vogt Ceramic Components, and CeramTec - all from Germany, CoorsTek from the USA, and Nishimura Advanced Ceramics (Japan) which in addition to producing CIM parts also supplies CIM and MIM feedstock.

Exhibitors producing or supplying Metal Injection Moulded parts include: USD Formteiltechnik, Oesterle GmbH, and Schunk Group (Germany), Sintex (Denmark), Indo-MIM (India), Precipart SA and Maxon motor AG both from Switzerland, Hunan Injection High Technology (China), and Lap Keung Precision (Hong Kong). Leading powder technology research organisation Fraunhofer-IFAM (Germany) will also be exhibiting.

www.hannovermesse.de

DeburringEXPO trade fair to highlight precision surface finishing

DeburringEXPO, the only trade fair to deal exclusively with the removal of burrs and the production of precision surface finishes, will be held at the Karlsruhe Exhibition Centre, Karlsruhe, Germany, from October 8-10, 2019.

"As of mid-January 2019, more than 100 exhibitors from ten countries had already made firm bookings for the exhibition. The solutions offered by the exhibiting companies are designed to efficiently and reproducibly fulfil current and future requirements for deburring, rounding and precision surface finishing in a great variety of industry sectors," reported Hartmut Herdin, Managing Director of fairXperts GmbH & Co KG, promoters of DeburringEXPO.

www.deburring-expo.com

Material data developed to help validate simulation tools for Ceramic Injection Moulding

Simulation tools are widely used in the development of new products by supporting product design, shortening development time, avoiding errors, and to help optimise the mould and injection moulding process. Process simulations are based on the Finite Element Analysis (FEA) method, and a number of commercial packages are available on the market including Autodesk Moldflow®, Moldex3D®, or Sigmasoft®. However, the simulation software developed to date for Powder Injection Moulding originates from the injection moulding of plastic feedstock and there is a lack of data allowing simulation of PIM where the feedstock comprises a mixture of a binder and powder which show significantly different properties to pure or even filled plastics. A collaborative research project undertaken at the Technical University of Denmark (DTU) in Lyngby, the University of Applied Sciences Northwestern Switzerland FHNW, Windisch, and Karlsruhe Institute of Technology (KIT), Germany, focused on a broad and comprehensive characterisation of two ceramic feedstocks with the material data obtained potentially allowing the development of material models for the simulation of mould filling during injection moulding. The results of their work have been published in a paper by Guido Tosello, *et al*, in the *International Journal of Advanced Manufacturing Technology* (online January 2, 2019), 16pp.

The authors stated that powder feedstocks can be defined as extremely filled plastics, where the binder provides the required viscous properties and acts as carrier for the rigid powder particles. The powder particles can, however, contribute to a large extent to the volume of the feedstock influencing the flow and viscosity because of the complex interaction between the binder and the particles. The powder particles, in contrast to the binder, can be incompressible and can carry much more momentum due to their weight. Furthermore, their size and shape affects the viscosity of powder containing feedstocks, which results in noticeably different flow properties compared to pure plastics. As a consequence of these differences, the developed simulation models for the viscosity of plastic feedstock are often insufficient to adequately describe the viscous nature of PIM feedstocks. Therefore, some commercial software providers, for example Sigmasoft, have implemented subroutines specially related to PIM.

In addition to viscosity, information is also required on the thermodynamic properties of the powder feedstock to allow computer simulations of the injection moulding process. These properties, the authors state, can be derived from the equation of state of the material which links pressure, specific volume and temperature.

Two ceramic powder feedstocks were used by the researchers to develop the required data for simulations. One was a commercial Catamold® grade TZP-A formerly distributed by BASF, Germany, which is a based on a polyacetal binder used with optimal ZrO_2 powder loadings determined as 81 wt.% (50 vol.%). The second was a custom-made feedstock 'GoMikro ZrO_2,' the research equivalent of the Catamold feedstock, which was compounded onsite at the Karlsruhe Institute of Technology (KIT) using a mixture of polyethylene (PE) and wax as the binder system. The feedstocks from KIT are actually made for micro Powder Injection Moulding and the GoMikro ZrO_2 should therefore provide good flow properties. The powder content was 87 wt.% (50 vol.%). Zirconium dioxide was selected because it is one of the most frequently used ceramics in PIM.

The specific heat capacity of the two ceramic feedstocks was measured by DSC with special attention to temperature dependency. The results for the two compounds were in the typical range for powder feedstocks with distinct peaks attributed to the melting temperature of the binder components. The heat carried by the feedstock is less than for plastics and, in addition, is released more quickly.

Compared to the pure plastic binder, the authors found that the powder feedstocks show, as expected, a greater thermal conductivity. The lower heat capacity and higher thermal conductivity can both be an

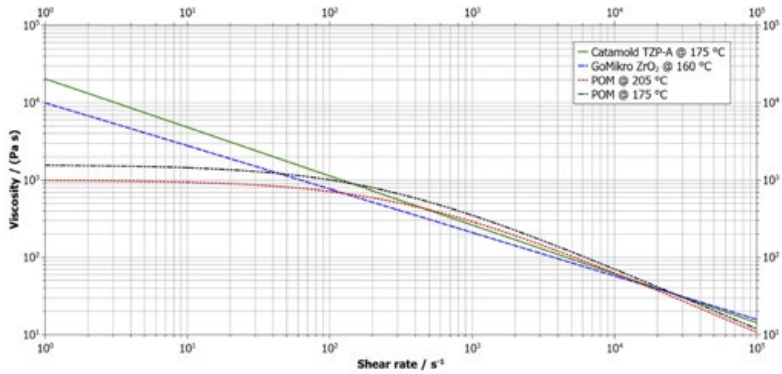

Fig. 1 Fitted viscosity curves of the investigated feedstocks at their typical processing temperature and reference curves of POM (From paper 'Comprehensive characterisation and material modelling for ceramic injection moulding simulation performance validations' by G. Tosello, et al. The International Journal of Advanced Manufacturing Technology, published online 2 January 2019. 16pp)

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issue during the filling phase. Both effects can lead to an increased risk of premature solidification and short shots. as well as larger pressure drops.

The viscosity of the feedstocks was successfully measured by means of a high-pressure capillary rheometer which determined the shear rate and shear stress based on the measurement of the pressure drop over the capillary and a given flow rate. The results of the viscosity measurements and the subsequent fitting of the viscosity are shown in Fig. 1, where they are compared to typical values of the pure POM binder of the Catamold feedstock. The authors found that GoMikro feedstock shows a lower viscosity than the POM at medium viscosity values and lower than the Catamold over almost the entire range, which proves its applicability for thin-walled and micro plastic parts.

The collected material data was used to create a new material model which the authors stated could be used to assess the performance of state-of-the-art simulation software.

The geometry used for the validation of the Powder Injection Moulding simulations was a double spiral test geometry shown in Fig. 2. The two spirals were symmetrical and comprised the actual spirals and a feed system with a sprue and a sprue gate, i.e., without a runner. The flow entered the cavity directly from the sprue. It is also equipped with a sprue puller. The cross-section of the spiral tube had a nominal thickness of 1.0 mm and a nominal width of 2.6 mm. The maximum flow length was about 100 mm at the centre of the flow path. The flow spiral could be classified as a micro precision part because of the tight tolerances in the micrometre range.

The authors used an advanced mould with a sensor array allowing for in-process monitoring and characterisation of the pressure and temperature evolution in the cavity live during the filling phase of the injection moulding process. The injection moulding machine used also monitored the applied injection pressure of the hydraulic drive. All tested feedstocks caused very high injection pressures near the machine's nominal maximum pressure.

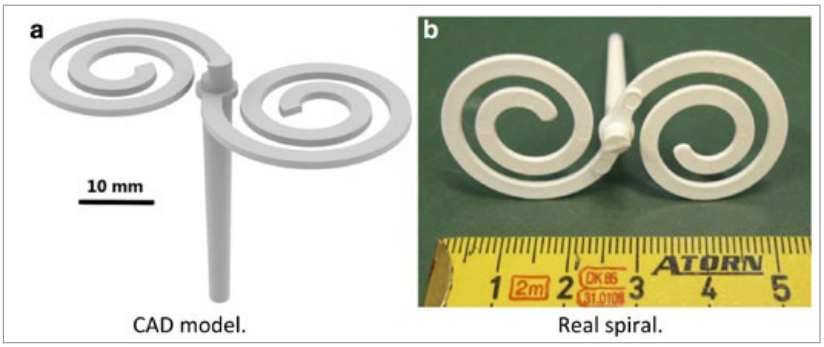

Fig. 2 CAD model and real part of the test spiral used for PIM simulations and experiments. (From paper 'Comprehensive characterisation and material modelling for ceramic injection moulding simulation performance validations' by G. Tosello, et al. The International Journal of Advanced Manufacturing Technology, published online 2 January 2019. 16pp)

The flow length was evaluated by an angular measurement of the spirals from which the spiral length could be calculated. The melt and mould temperatures of the feedstocks were chosen as high as allowed to achieve the best filling and largest flow length. Table 1 shows the process settings for the moulding of the double spiral for the two CIM feedstocks and Table 2 shows the experimental results for the full shots of the moulded test spirals.

The goal was to investigate the pressure development in the cavity as well as to evaluate the flow length and

Parameter	Catamold TZP-A	GoMikro ZrO_2
Nozzle temperature/°C	180	200
Barrel temperature/°C	172 – 180	178 – 200
Mold temperature/°C	145	51
Injection speed/mm/s	35	40
Packing time/s	2.7	2.7
Cooling time/s	35	35

Table 1 Process settings for the moulding of the double spiral geometry with the characterised feedstocks. (From paper 'Comprehensive characterisation and material modelling for ceramic injection moulding simulation performance validations' by G. Tosello, et al. The International Journal of Advanced Manufacturing Technology, published online 2 January 2019. 16pp)

Compound	Fill time/s	Fill pressure/MPa	Flow length/mm
Catamold TZP-A	0.45	262.5 ± 3.6	95
GoMikro ZrO_2	0.42	263.3 ± 1.2	100

Table 2 Experimental results for the full shots of the moulded test spirals. (From paper 'Comprehensive characterisation and material modelling for ceramic injection moulding simulation performance validations' by G. Tosello, et al. The International Journal of Advanced Manufacturing Technology, published online 2 January 2019. 16pp)

thus the applicability of the feedstocks to micro structures. Fig. 3 compares of the moulded spirals for each CIM feedstock (left: Catamold TZP-A and right: GoMikro ZrO_2).

The spiral part was modelled together with the feed system in ASMI software to investigate the predicted fill time and fill pressure, and to compare this with the experimental data from the pressure curves of the machine and the sensors in the mould. The simulations of the double spiral using Catamold were compared to the experiments and the researchers also introduced the monitoring of the speed profile during the moulding to the simulations to gain better results in comparison to a simple constant speed profile. They stated that from the investigation of the injection pressure measured by the machine and by the sensors it was revealed that the simulations underestimated both the pressure levels and fill times for the Catamold feedstock.

The main reason for the reported discrepancies was most likely the inadequate viscosity model, i.e. the regular Cross-WLF model. The simulation of Powder Injection Moulding had, therefore, to be evaluated as critical and not entirely reliable with the used ASMI software. However, adapted viscosity models and access to the core of the software provide the potential for enhancements and are recommended as scope of current and future work. For more information contact volker.piotter@kit.edu or guto@mek.dtu.dk.

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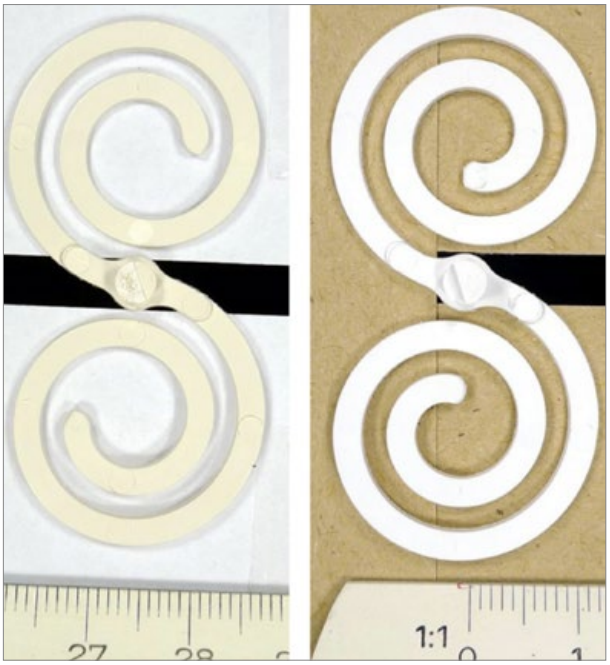

Fig. 3 Comparison of the moulded spirals (left: Catamold TZP-A and right: GoMikro ZrO2) (From paper 'Comprehensive characterisation and material modelling for ceramic injection moulding simulation performance validations' by G. Tosello, et al. The International Journal of Advanced Manufacturing Technology, published online 2 January 2019. 16pp)

Tekna to begin powder production in Europe

Tekna, a subsidiary of Arendals Fossekompani ASA with its headquarters located in Sherbrooke, Canada, has announced a €5 million investment for the production of spherical powders intended for Metal Injection Moulding and Additive Manufacturing at its new industrial site in Mâcon, France. The site can accommodate various specialised plasma atomisers, enabling the manufacturing of a variety of strategic materials and alloys.

The production volume on site will be capable of achieving 400 to 500 tons, increasing Tekna's annual global capacity to over 1000 tons.

The company stated that replicating its production means and processes in Europe will ensure that Tekna perfectly duplicates its powder production activities and provides a continuous supply to its clients. In addition to the start-up of powder production, the new site hosts its European Customer Service Centre and a laboratory dedicated to quality assurance and the development of new powders.

"In line with the rapid growth of our activities, this major investment enables us to provide our clients with closer support while accounting for the safeguarding of their supply chain and volume expansion, in addition to controlling costs and logistical risks," stated Rémy Pontone, VP, Sales and Marketing, and Managing Director of Tekna Plasma Europe SAS.

"At Tekna, we guarantee our clients high-quality products that are always delivered on schedule at the best costs. I would like to acknowledge the technical and manufacturing teams on site who have contributed to successfully completing this strategic project. As a result, it is our clients who are the big winners," added Tekna's CEO, Luc Dionne.

Tekna uses a plasma spheroidisation process to manufacture a range of metal powders. It also produces a range of turnkey plasma systems for the production of metal powders.

www.tekna.com

Furnace and heat treat specialist Ipsen appoints Somary as group CEO

Ipsen International Holding GmbH, Kleve, Germany, has announced the appointment of Geoffrey Somary as CEO of Ipsen Group worldwide. Somary succeeds former Thorsten Krüger, who served as CEO from 2013-2019 and who has now moved to the company's Advisory Board.

Since 2005, Somary has held various senior positions within Ipsen and was said to have been closely involved with customers and with team members of the company. He has reportedly demonstrated the ability to bring together employees of different cultures in a way that delivers the best possible solutions to Ipsen customers.

The Advisory Board expressed its thanks to Krüger for his contributions to the company since his appointment in 2013. It was stated that, in shifting his role from operational to advisory, he will continue to support the further development of the company.

Ipsen designs and manufactures industrial vacuum and atmosphere heat-treating systems, supervisory control systems and predictive maintenance platforms for a wide variety of industries, including aerospace, automotive, commercial heat treating, energy and medical. The group has production locations in Europe, North America and Asia, along with representation in thirty-four countries.

www.ipsenUSA.com

ALD expanding Hanau plant

ALD Vacuum Technologies is to expand its plant site in Hanau, Germany, with a new office building and technical centre. The move into the new buildings has been planned for the end of 2019. In 2016, ALD moved to the Fraunhofer Science Park in Hanau, where it now employs five-hundred staff. "Currently, we have to move closer together and even create interim solutions in order to find a place for all employees. We are therefore very much looking forward to moving into the new buildings this year," stated Markus Holz, ALD's CEO. The ALD R&D Centre, previously located in one of ALD's assembly halls, will be located in the new technical centre.

www.ald-vt.com

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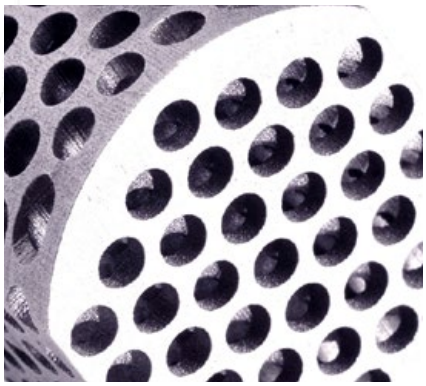

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Project studies oxidation behaviour of IN 713 Ni-base superalloys made by MIM

In the December 2016 issue of *PIM International* (Vol. 10, No. 4, pp 61-62) we reported on the results of research into the influence of heat treatment on the mechanical properties of as-sintered IN 713LC Ni-base superalloys produced by the Metal Injection Moulding process. The work was carried out within the framework of the BMWi (Bundesministerium für Wirtschaft und Energie/ Federal Ministry for Economic Affairs and Energy) funded LuFo project RHinnoVer (funding code: 20T1111).

A further aspect of this research project has been the study of the oxidation behaviour of as-sintered superalloy IN 713 produced by MIM because mechanical properties can also be affected by the oxidation resistance of this material, particularly at the high service temperatures of these superalloys when used in aero engines and land based gas turbines. Metal Injection Moulding is seen as an attractive and cost effective alternative to casting for the volume production of complex shape, high performance superalloy components.

Naicheng Sheng, Andreas Meyer, Ralf Rettig, Robert F. Singer (Friedrich-Alexander University of Erlangen-Nuremberg), and Katharina Horke (Rolls Royce Deutschland Ltd & Co KG), reported in their paper 'Oxidation Behaviour of Superalloy IN 713 Fabricated by Metal Injection Moulding' and published in *Oxidation of Metals*, 6 September 2018, 17pp, that Cr and Al are usually added to superalloys in order to form dense and slowly growing protective oxide layers. It is these oxide layers, such as Al_2O_3 or Cr_2O_3, which help the alloy to improve the resistance against the oxidation and corrosion environment at high temperatures.

The IN 713 superalloy grade studied contains 12 wt.% Cr and 5.8 wt.% Al and will form the growing Al_2O_3 protective oxide scale layer during service. Carbides can react with the oxygen during oxide scale formation and the selective oxidation of carbides can lead to formation of protrusions and cracks in the outer layer. In this way the protective effect of the oxide scale is weakened. The focus of this research was, therefore, to compare the influence of C content on oxidation behaviour in three MIM produced IN 713 superalloys with a standard cast plus hot isostatically pressed (cast+HIP) IN 713LC.

The compositions of the four IN 713 superalloys are shown in Table 1. Powders with high, medium and low C content are termed MIM IN 713C, MIM IN 713LC and MIM IN 713VLC, respectively. Plate shape MIM specimens from these powders were prepared by injection moulding and then sintered by Schunk Sintermetalltechnik GmbH, Thale, Germany. The cast + HIP material was produced in cylindrical bar form by Zollern GmbH.

The MIM samples were used for oxidation tests in the as-sintered state. Before oxidation, all materials were machined into two different dimensions. The first group (40 × 7 × 2 mm) was used for oxidation in furnaces at 800°C and 900°C for up to 300 h. The second group (10 × 10 × 2 mm) was used for oxidation tests in a thermo-gravimetric analyser at 1000°C and 1100°C for up to 60 h. The surface roughness Ra of machined and ground samples is below 0.3 µm. All the samples were oxidized using 80% N_2 and 20% O_2 artificial dry air.

	Cast + HIP IN 713LC		MIM IN 713VLC		MIM IN 713LC		MIM IN 713C	
	wt.%	at.%	wt.%	at.%	wt.%	at.%	wt.%	at.%
Ni	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.
Cr	12.0	12.8	12.0	12.8	12.0	12.8	12.0	12.8
Al	5.8	11.9	5.8	11.9	5.8	11.9	5.8	11.9
Mo	4.3	2.5	4.3	2.5	4.3	2.5	4.3	2.5
Ti	0.7	0.8	0.7	0.8	0.7	0.8	0.7	0.8
Nb	2.0	1.2	2.0	1.2	2.0	1.2	2.0	1.2
Zr	0.06	0.04	0.06	0.04	0.06	0.04	0.06	0.04
B	0.007	0.036	0.007	0.036	0.007	0.036	0.007	0.036
C	0.07	0.32						
C (powder)			0.0038	0.019	0.012	0.056	0.15	0.69
C (sintered)			0.03	0.14	0.07	0.32	0.15	0.69

Table 1 Compositions of alloys used for oxidation process. The composition of the MIM IN 713 alloys cites the same content as Cast+HIP IN 713LC except for C due to industrial confidentiality reasons. (N. Sheng, et al 'Oxidation Behaviour of Superalloy IN 713 Fabricated by Metal Injection Moulding' Oxidation of Metals, published online 6 September 2018, 17pp)

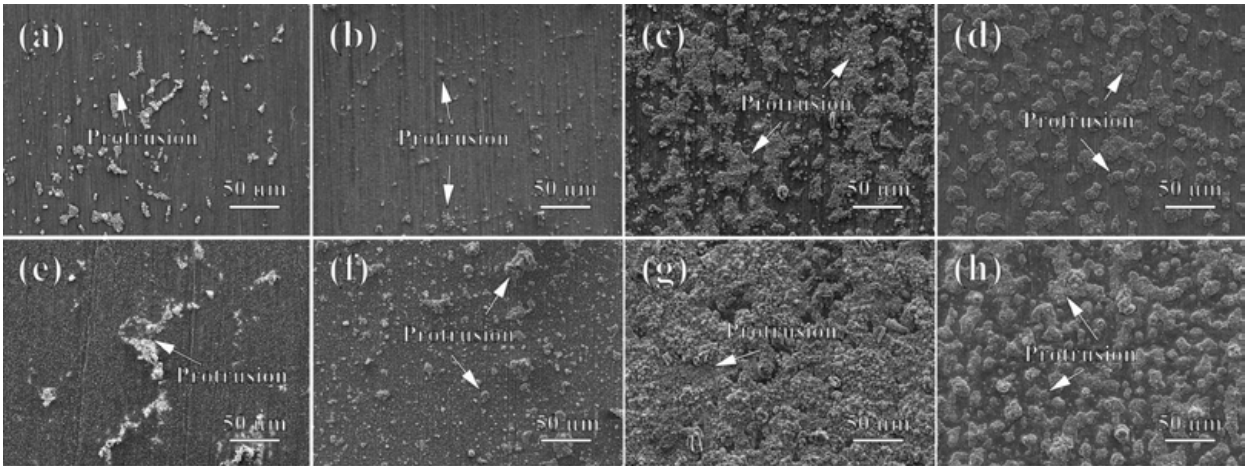

Fig. 1 Surface morphologies after oxidation at 800°C (a) Cast + HIP IN 713LC, (b) MIM IN 713VLC, (c) MIM IN 73LC, (d) MIM IN 713C, and 900°C (e) Cast + HIP IN 713LC, (f) MIM IN 713VLC, (g) MIM IN 73LC, (h) MIM IN 713C for 300 h. (N. Sheng, et al 'Oxidation Behaviour of Superalloy IN 713 Fabricated by Metal Injection Moulding' Oxidation of Metals, published online 6 September 2018, 17pp)

The tests were interrupted at predetermined times for measurement of weight gain during oxidation. The average weight gain of the three samples was calculated for measurement of the oxidation kinetics. In the thermo-gravimetric analyser testing of the second group, at 1000°C and 1100°C, only one sample was tested and the weight gain was automatically recorded by the equipment every 5 s. After oxidation, the surface morphologies were observed using scanning electron microscopy (SEM).

The initial grain morphologies of the different alloys showed that the grains in cast + HIP alloy are rather irregular and much larger than the MIM alloys. The cast+HIP alloy also still exhibits dendrite structures even after HIP. Fine and equiaxed grains are observed in as-sintered MIM alloys with IN 713VLC alloy having a larger grain size than the other two MIM alloys since the lower C content will be beneficial for grain growth during sintering process. Besides the grain structures, the microstructures, such as porosities, precipitates and carbides, in cast + HIP and MIM alloys are also different as reported in the paper.

The authors found that protective Al_2O_3 layers and surface protrusions are formed in all the four alloys after oxidation at 800°C and 900°C for 300 h (Fig. 1). The amount and morphology of protrusions, which are nodular shaped and grow on the Al_2O_3 layer, vary in different alloys. More protrusions are formed in MIM IN 713LC and MIM IN 713C than the cast+HIP IN 713LC and MIM IN 713VLC. The amount of surface protrusions will increase in MIM IN 713 superalloys with the increase of C content.

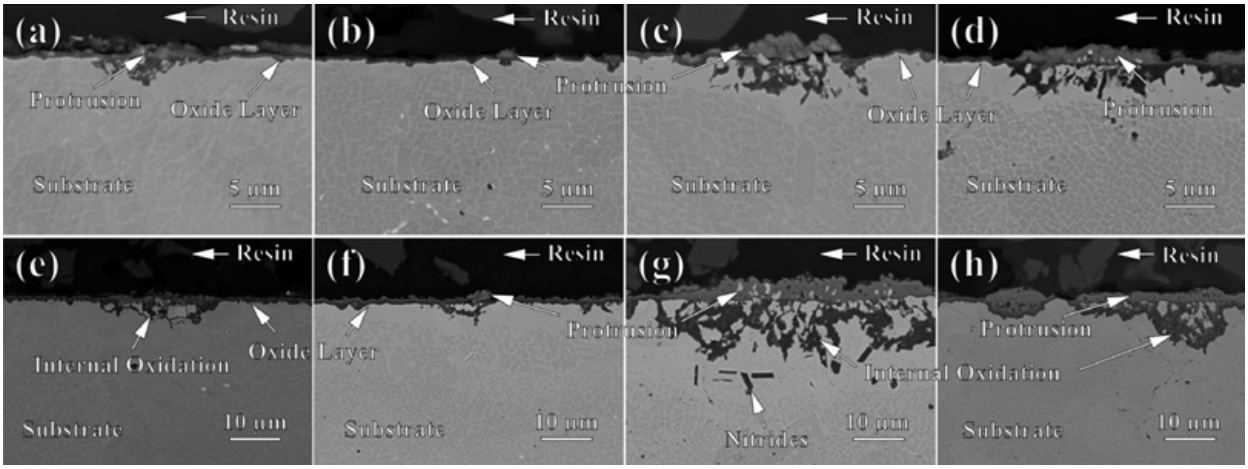

Fig. 2 Cross section morphologies after oxidation at 800°C (a) Cast + HIP IN 713LC, (b) MIM IN 713VLC, (c) MIM IN 73LC, (d) MIM IN 713C, and 900°C (e) Cast + HIP IN 713LC, (f) MIM IN 713VLC, (g) MIM IN 73LC, (h) MIM IN 713C for 300 h. (N. Sheng, et al 'Oxidation Behaviour of Superalloy IN 713 Fabricated by Metal Injection Moulding' Oxidation of Metals, published online 6 September 2018, 17pp)

Surface morphologies and surface protrusions of specimens after oxidation at 1000°C for 60 h and 1100°C for 60 h exhibit similar tendency as for the lower temperatures. However, the morphology of the oxide layers changed at 1100°C. In cast+HIP IN 713LC, more protrusions are formed and spallation of the protrusion is already observed after cooling from 1100°C. Interestingly, the oxide layer of MIM IN 713VLC is still much more stable than the oxide layers of the other three alloys.

The authors also studied the cross-sectional views of the internal microstructures of the four alloys after oxidation at 800°C and 900°C for 300 h in order to understand the oxidation mechanism (Fig. 2). Al_2O_3 layers can already be observed in all the alloys, and surface protrusions on the Al_2O_3 layer are also observed. MIM IN 713VLC was found to exhibit the most stable and adhesive Al_2O_3 layer after oxidation for 300 h. The Al_2O_3 layer in cast+HIP IN 713LC is also quite stable, but the protrusions are larger than those in MIM IN 713VLC alloy. Cross sections of specimens after oxidation at 1000°C and 1100°C for 60 h were also examined. At 1000°C, no obvious spallation was observed in different alloys, but severe spallation of MIM IN 713LC and MIM IN 713C occurred during cooling from 1100°C. At 1100°C, the Al_2O_3 layer in MIM IN 713VLC remains stable and adhesive.

The authors found that the stability and oxidation resistance of the Al_2O_3 protective layer is greatly reduced during oxidation due to the combined loss of continuity of the Al_2O_3 layer and the formation of surface protrusions. The additional stress coming from these protrusions may lead to some cracks in the Al_2O_3 layer and these cracks are detrimental to the oxidation resistance of the alloys. There is always internal oxidation below the protrusions. Oxygen could diffuse faster through these protrusions into the substrate and lead to further oxidation of Al. The internal oxidation becomes more severe when the protrusion is larger since more O can diffuse into the substrate. The expansion of carbides could also introduce stresses surrounding the protrusions resulting in formation of cracks.

The authors stated that increasing C content leads to increase of weight gain in MIM alloys during oxidation from 800 to 1100°C, with MIM IN 713VLC exhibiting the lowest weight gain in all the temperatures among the MIM alloys. This is due to the stability of the protective Al_2O_3 layer during the oxidation of this alloy. The C content in as-sintered MIM IN 713VLC is quite low (0.03 wt%) resulting in few carbide particles. Therefore, relatively few surface protrusions are formed due to the selective oxidation of these carbide particles and the protrusions did not significantly affect the protective Al_2O_3 layer. A continuous Al_2O_3 layer can still form below the protrusions even after the carbides are oxidised. The low quantity of protrusions in MIM IN713VLC, might also help to reduce the inward diffusion of O to the substrate.

The authors concluded that MIM IN 713C and MIM IN 713LC with high and medium C contents respectively, exhibit poorer oxidation properties than cast+HIP IN 713LC, but MIM IN 713VLC (very low carbon) shows a comparable oxidation resistance with cast+HIP IN 713LC. Therefore, decreasing the C content to avoid severe oxidation degradation due to the carbide forming elements such as Nb and Ti, may be a guideline for the future development of nickel base superalloys suitable for production by the MIM process.

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MPIF's 2019 Distinguished Service to Powder Metallurgy Awards announced

The Metal Powder Industries Federation (MPIF) Awards Committee has announced the recipients of the 2019 MPIF Distinguished Service to Powder Metallurgy Award, which recognises individuals who have actively served the North American PM industry for at least twenty-five years and whose peers believe they deserve special recognition.

The awards ceremony will take place during POWDERMET2019 and AMPM2019 on June 25, 2019, at the Industry Luncheon in Phoenix, Arizona, USA.

The 2019 award recipients are as follows:

- Denis Christopherson, PMT, Federal-Mogul Powertrain
- Zhigang (Zak) Fang, FAPMI, University of Utah
- Robert M Gasior, Arconic Technical Center
- Ryuichiro Goto, Engineered Sintered Components
- William A Heath, PMT, MPP
- Stephen J Lanzel, Catalus Corporation
- Deepak Madan, Luxfer Magtech
- David Milligan, North American Höganäs
- Thomas Pfingstler, Atlas Pressed Metals
- Daniel P Reardon, Abbott Furnace Company
- Christopher T Schade, Hoeganaes Corporation
- Michael Stucky, Norwood Injection Technologies
- C James Trombino, MPIF (retired)

www.mpif.org

Report highlights promising production technologies using advanced nanostructured materials

The European Union has identified within its innovation priorities for the 7th EU Framework Research Programme, the need to scale up the most promising material production technologies from R&D to pilot production level in order to progress the manufacture of cutting edge materials using novel new production processes.

To meet this objective the EU selected and financially supported to the sum of €5.354 million a research project designated 'PilotManu' involving ten partners from research organisations around Europe as well as industrial SME partners. The 'PilotManu' project was aimed at developing a pilot manufacturing line for the production of highly innovative materials cutting across many technology areas, but its core objective was to upscale the current R&D level high energy ball milling – or mechanical alloying – technology owned by MBN Nanomateriala Spa, Italy, into a pilot manufacturing plant for a range of nano sized powders.

The recently published Final Report for the PilotManu project stated that existing manufacturing facilities for the production of advanced and nano-structured materials by high energy ball milling (HEBM) suffer from low productivity and high cost which are key barriers for the application of these materials in new and innovative applications.

The new improved HEBM pilot plant developed by the PilotManu project, which started operating at MBN Nanomaterials in 2018, has allowed the scaling up of the powder production process by a factor of ten, whilst also reducing power usage by 50%. A wide range of novel systems ranging from polymer nanocomposites, to ceramic metal composites and nanostructured metal powder alloys were produced with fine and homogeneous chemical distribution of elements and 'ultrafine' crystalline structure. The nanoscale powders produced showed significant improvement of material performance and physical-chemical-mechanical properties compared to bulk scale materials.

In order to validate the new HEBM pilot machine, processing tests have been performed and compared with the same powder produced by current HEBM facilities. A number of powder systems have been selected as representative materials for the physical-chemical point of view and for product applications in the three project product lines:

- FeCu alloy and FeP based nano alloy powders for grinding/diamond tool applications using hot pressing and spark plasma sintering (SPS)
- Ti-WC and WCCoCrAl Cermets for thermal spraying of coatings
- Nano steel, WC-Co and Ti- and Ni powder alloys for additive manufacturing using direct laser sintering and selective laser sintering.

Although Powder Injection Moulding was not specifically mentioned as one of the advanced manufacturing processes, it is obvious that PIM processing would also benefit from using the new, lower cost nano powders to produce microPIM parts for a number of end-user sectors.

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CHINA'S LEADING SUPPLIER OF MIM POWDERS

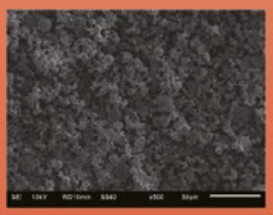
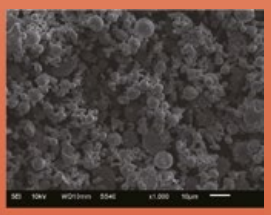
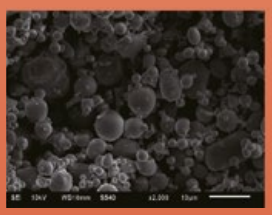
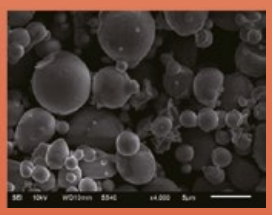
ADOPTING ADVANCED GAS AND WATER COMBINED ATOMIZATION TECHNOLOGY

LD METAL POWDERS

Yingtan Longding New Materials & Technology Co., Ltd - Beijing Branch

The company provides various types of structural material powders, magnetic material powders, and other alloy powders in a variety of particle sizes and tap density based on the demands of the customers. The product line includes 316L, 304L, 17-4PH, 4J29, F75, HK30, 420W, 440C, Fe2Ni, 4140, and FeSi. The customers have received the products with high acclaim

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

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The evolution of Powder Injection Moulding: Past perspectives and future growth

Understanding the evolution of materials and applications for Powder Injection Moulding, along with identifying trends and key technology drivers, can go some way towards helping us understand future opportunities for the industry. Prof Randall German considers the growth of MIM and CIM from the technology's early commercialisation to the recent boom in Asia on the back of the consumer electronics market. Opportunities to help sustain technology growth are presented, ranging from new materials to process innovations and applications.

This article examines the current status of Powder Injection Moulding and reviews the pathway taken since the 1970s. Looking forward, three directions can be identified to further grow the field. Firstly, opportunities for growth through new materials require a focus on sensitive chemistries in high-temperature alloys, such as titanium aluminide. This is quite different from the early successes with carbon-free materials such as alumina and stainless steel.

New applications of merit are identified in terms of long-wave markets, especially where structural response is dominant. Examples include medical implants, heat sinks and heat pipes for thermal management, and aerospace components.

The third growth opportunity is associated with processing advances including steps leading to improved dimensional control, higher process yield, reduced time to market, integrated Hot Isostatic Pressing (HIP) and fast sintering cycles.

Historical perspective

The idea of injection moulding metal powders arose in the 1970s following earlier demonstrations in the 1940s with ceramics. The first demonstrations of Ceramic Injection Moulding were for automotive spark plug bodies, electrical insulators and dinnerware. Much of the early work failed to reach significant commercial levels. Thus, the first sales assessment was not until 1987, reporting the status for 1986. These early reports identified twenty-nine firms involved in PIM, of which twenty-two were in production, generating $9.1 million in annual sales. Table 1 compares that situation with what is the 2019 status.

The global growth of Powder Injection Moulding 1986-2019			
	1986	2019	Growth rate %/year
Number of production firms	22	635	11
Global sales, $ million	9	3,000	19
Average sales per firm, $ million	0.4	4.7	8
Employment	164	26,000	17

Table 1 The growth of PIM by number of firms, sales and employment

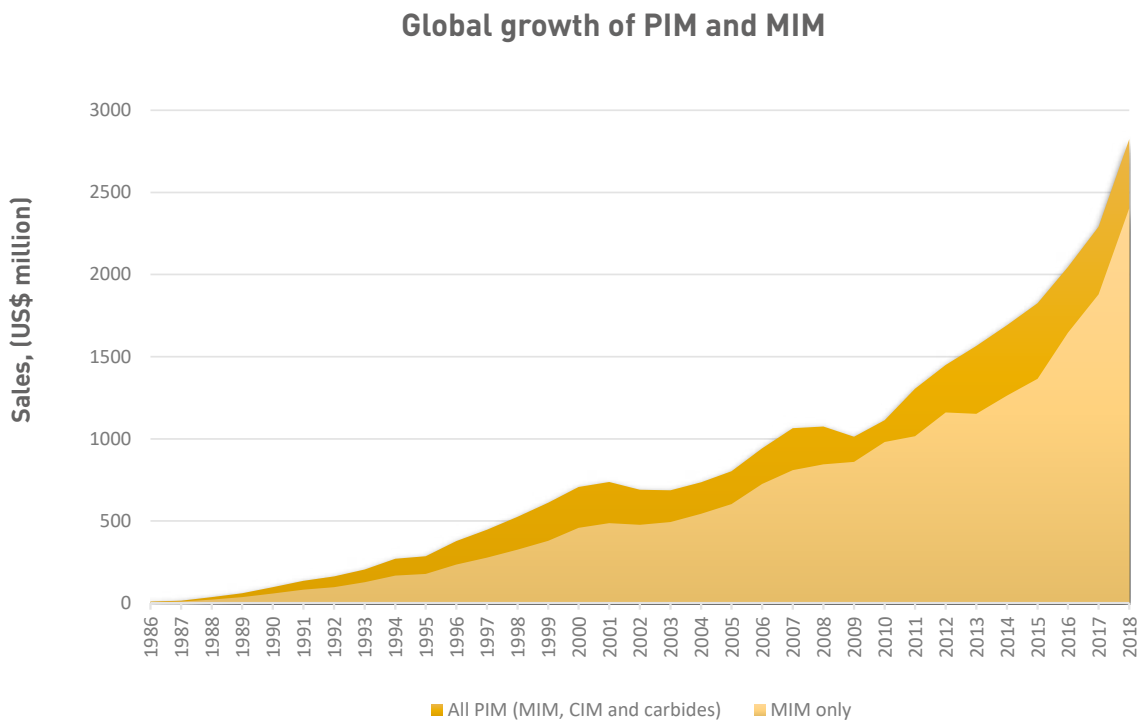

Fig. 1 Sales figures for Metal Injection Moulding and all Powder Injection Moulding from 1986 to 2018

Fig. 1 plots the global sales since the first assessment in 1986. Note that the growth in airfoil casting cores provided a strong boost to PIM by the early 1990s. For 1986, global PIM industry sales averaged $0.4 million per production firm. The largest reported $3 million in sales with $7 million in loss. That firm soon expired. By 2019 the average is expected to reach $4.72 million per firm, up about 5% from 2018. For comparison, market studies in 2007 and 2012 reported the industry average stalled at about $3.3 million per firm.

The growth rate in overall industry sales averages 19% per year; however, this sales growth has not been uniform. Early years exhibited peaks of 32% sales increase per year. While this was happening, the number of production firms grew too, at about 11% per year. Thus, because expanding sales were spread over more actors, the growth in sales per firm was a more modest 8% per year. Unsurprisingly, industry leaders complained they were not seeing rapid growth. This is because a significant portion of the growth went to new firms.

The growth of MIM in India and China has held average sales per employee on a global basis to a relatively low $110,000 per employee per year. Production operations in China report from $30,000 to $55,000 per year per employee. Likewise, production in India is not much higher, averaging annual sales of $67,000 per employee. On the other hand, in Europe and North America, these values are much higher.

Current status

The PIM industry has excelled in the production of complex shapes, in large production quantities, for relatively small geometries. An excellent example is shown in Fig. 2; a spindly, thin wall structure.

The old adage for MIM component identification remains accurate: a part should ideally be 'about the size of a golf ball'. Various audits of designs reaching production find a typical component consists of 200,000 pieces per year, with a wall thickness of 1 to 3 mm. The median design mass is under 10 g. Recent estimates, based on the number of parts in production rather than number of designs, suggest 6 g is now typical. This lower mass is influenced by the incredibly large number of cell phone components. For example, Apple sold 217 million smartphones in 2018 and the MIM parts used in their manufacture reportedly required 988 tons of powder. The average MIM content per phone is probably fifteen to twenty parts, with a total mass under 5 g. Analysis of nineteen current production parts shows the largest wall thickness is 2.2 mm and the largest dimension is 19.2 mm. These small components skew production averages toward small parts.

Ponder, on the other hand, prior efforts to produce golf clubs using MIM. Examples abound, involving some of the top names in the industry. Putters went into

production using stainless steel and titanium, drivers reached field trials in titanium, but these larger parts failed to be cost competitive with other technologies. Now we have a stainless steel wedge reported to weigh nearly 300 g made by MIM. It will be curious to see if this time golf stays with MIM, since the component is large by MIM standards.

Thus, outside of the golf wedge, most current MIM and CIM emphasises smaller components with three-dimensional complexity, usually produced in quantities of hundreds of thousands per year. This of course leaves an opening for Additive Manufacturing for lower production quantities.

As the old saying goes, water flows downhill. In that sense, the PIM business migrates to low-cost regions. Thus, we see China reportedly approaching $1 billion in annual sales, while the rest of Asia (including India) is approaching $700 million. Europe and North America reach $1.2 billion of combined metal and ceramic production. Over this industry, success is not uniform; 10% of the firms control two-thirds of the sales and enjoy 80% of the industry profits.

These facts are important because significant changes are coming, and to grow PIM in general requires some changes – improvements in production, applications and materials. Some thoughts on these changes follow in this article. After all, Apple has been fairly forthright in its desire to move toward ceramics due to better phone reception and lighter devices, with the elimination of several of the MIM parts, especially buttons and plugs. Thus, the PIM industry is being forced to change by its largest customer.

Fig. 2 An example of a small component fabricated by Metal Injection Moulding to demonstrate the industry's capabilities

Fig. 3 Carbon control was a necessary technology gain needed to fabricate this cemented carbide splitter, one of the early components fabricated by Powder Injection Moulding

PIM materials: Past and present

It is instructive to understand how material use for Powder Injection Moulding has evolved. Two categories were early successes. The first were the oxide ceramics, notably alumina, which remains a mainstay for Ceramic Injection Moulding. For metals, early products relied on the available carbonyl powders, since atomisation was not producing the necessary small-sized alloy powders. Thus, iron-nickel soft magnetic compositions were an ideal starting point. The magnetic performance was best with no carbon, so thermal debinding in air using 120 hour slow heating was a starting point. The addition of a carbon source provided low alloy, heat-treatable steels. Later, as atomised stainless steel powders became available, other materials without carbon became popular, such as 316L. In other words, zero carbon alloys were the early mainstay. When the automotive and firearm industries looked at MIM, they wanted heat treatable steels. To retain carbon in the final product required a new processing sophistication, which in turn helped mature the industry.

Pre-alloyed stainless steel powder was a by-product of Hot Isostatic Pressing as used to produce oilfield tubes for the North Sea. The atomised -325 mesh powder was too high in oxygen for HIP use, so that unused powder was taken up by MIM. Today, 316L and 17-4 PH account for 46% of

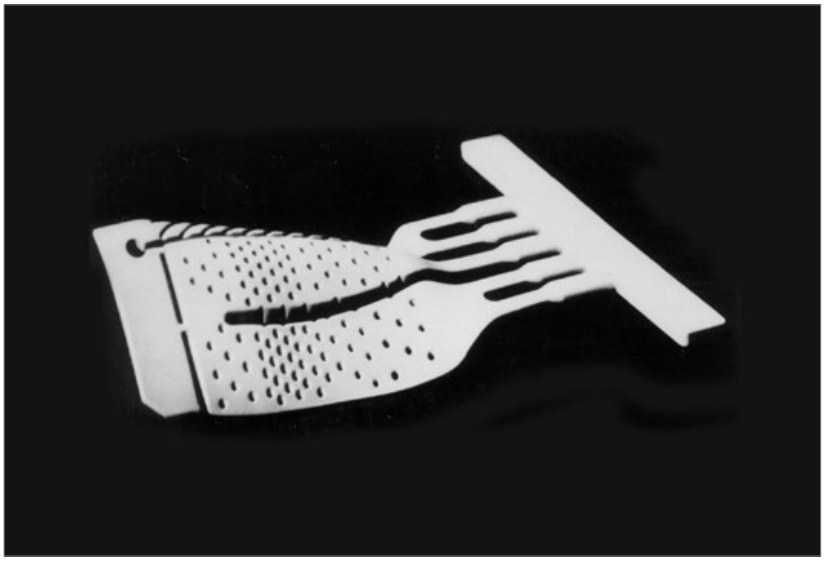

Fig. 4 An alumina casting core used as the template for forming cooling channels inside a single crystal superalloy turbine blade. Each core is dissolved from the casting, so it is only used once

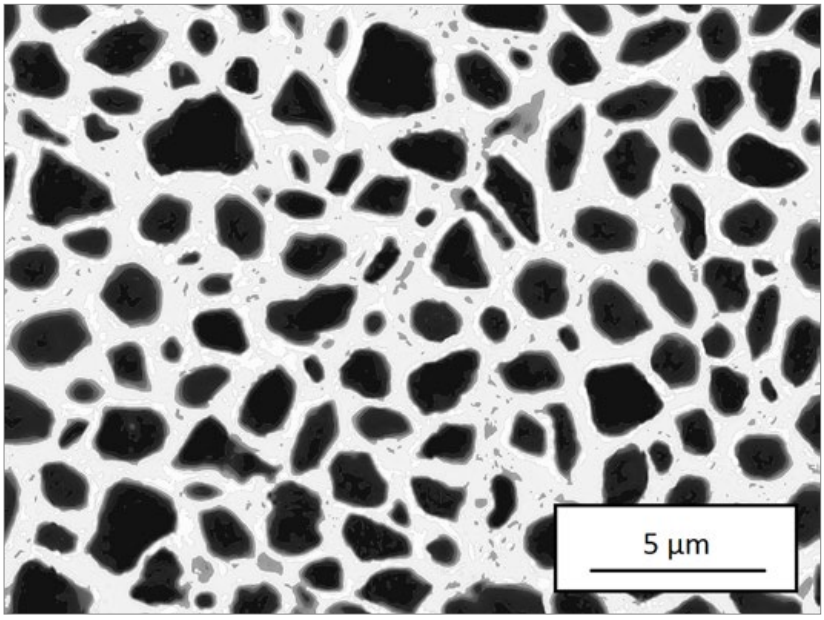

Fig. 5 This scanning electron micrograph shows the structure of a high-wear resistance composite microstructure consisting of alumina cores (black) and cemented carbide matrix

MIM industry sales. However, firearm and automotive applications favoured heat treatable steels with 0.4 to 0.8% carbon. Likewise, wear components similar to the splitter shown in Fig. 3 relied on cemented carbides, with even more carbon. Thus, carbon control to specific targets became a focus for the industry.

By the late 1980s, titanium and superalloys were under development. At the same time, ceramics tended to keep a focus on oxides, alumina, silica and zirconia, with some efforts in silicon nitride and silicon carbide. Only silicon carbide required attention to carbon.

In short, PIM materials started with no-carbon compositions and then moved to higher performance carbon containing compositions. In recent years almost all engineering materials have been demonstrated in Powder Injection Moulding, ranging from whitewares to titanium. In surveying the matrix of applications and materials, two clear directions emerge. First, almost 75% of the PIM components are structural alloys for use in industrial, medical, firearm, automotive, dental and consumer electronics uses. On the other hand, another 10% of the PIM components are refractory ceramics for high-temperature use, dominated by casting cores. One is shown in Fig. 4. Related applications are in melt handling, such as pouring spouts, filters and crucibles. Ceramic refractories are also needed for sintering and heat treating. Missing are the lower temperature materials, such as aluminium. The Powder Injection Moulding of aluminium was demonstrated twenty years ago, but due to high cost it has yet to displace traditional die casting. Clearly, PIM is aligned with higher melting temperature materials where die casting is not possible – stainless steel, steel, alumina, zirconia, tungsten, titanium, superalloy, cemented carbide, silicon nitride and iron-nickel.

Future PIM materials

This sets the stage for pondering the new materials that might add growth to PIM. High-temperature intermetallics are one option, and titanium aluminide compositions are very attractive. Injection moulding and sintering has been demonstrated for the TiAl compound alloyed with chromium and niobium. The theoretical density is 3.8 g/cm^3, yield strength is 1400 MPa, tensile strength is 1850 MPa, and both strength and toughness increase on heating up to 600°C. This implies the strength-to-weight ratio far exceeds current alloys. Applications include components for jet engines, turbochargers, diesel engines and power generation systems.

Another opportunity is with the FeCrAlY compositions (such as Fe-24Cr-8Al-0.5Y or Fe-20Cr-5Al-0.1Y). These alloys exhibit high strength at intermediate temperatures with excellent oxidation resistance. Nickel aluminides also fall into this category. These alloys are favoured for energy systems in power production and combustion engines. Tantalum is another medical material that is expensive, but largely ignored by injection moulding.

Particulate composites are in production using Powder Injection Moulding. The most common are tungsten alloys for inertial applications (cell phone vibrators, watch weights, fragmentation projectiles and golf club weights). Also, heat sinks and thermal management combinations exist, such as tungsten-copper. These materials combine low thermal expansion and high thermal conductivity as desired to avoid thermal fatigue. Other options, such as aluminium nitride with yttria, showed excellent properties, reaching 270 W/(mK) thermal conductivity, but were too expensive. However, tungsten-copper is heavy, so various options arise, including functional gradient heat sinks consisting of copper and aluminium nitride. Hybrid automobiles and computer servers are the first high-volume applications, but high-intensity solid state lighting is the mega market for heat dissipation materials.

In terms of wear resistance at intermediate temperatures, MIM enables the mixing of powders to create particulate composites. A high-performance version is shown in Fig. 5, consisting of alumina (dark) in a matrix of WC-Co (white). One variant is tool steel with reinforcing titanium carbide. These 'Ferro-TiC' alloys are applied in metalworking tools up to 600°C, but they are difficult to machine. This is an ideal case where Powder Injection Moulding of the mixed phases is applicable to shaping, followed by sintering for densification. These composites are often given a final densification step using Hot Isostatic Pressing.

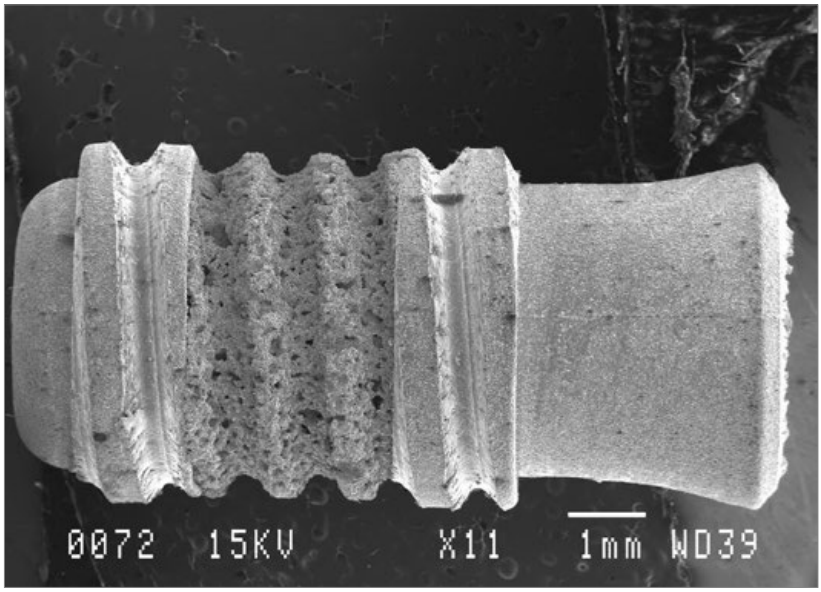

Fig. 6 Porous titanium dental implant fabricated by metal Powder Injection Moulding. Note the porosity is selectively located at the centre for tissue ingrowth

Porous metal and ceramic structures have been in production using injection moulding for several years. The early applications were in casting cores and filters. For the alumina casting core, an open pore structure enables rapid digestion to remove the ceramic. The resulting cooling channels inside the turbine component enable high combustion temperatures.

Filters are often simple shapes, so injection moulding is not justified based on shape complexity, but recent efforts have identified gains from the increased porosity that gives higher permeability. Controlled porosity is extended to implants, both dental and medical. Fig. 6 shows a scanning electron micrograph of a porous titanium structure designed for tissue ingrowth as a dental implant.

Generally, PIM is about mechanical properties in higher melting temperature materials, so it is inappropriate to push it toward alloys of aluminium, magnesium, or zinc. Likewise, efforts with glass injection moulding have largely failed. On the other hand, injection moulding is very successful for higher melting temperature materials (over 1400°C), such as tungsten alloys, cemented carbides, stainless steels, oxide ceramics of alumina and zirconia, and steels, superalloys, and cobalt-chromium alloys.

"Generally, PIM is about mechanical properties in higher melting temperature materials, so it is inappropriate to push it toward alloys of aluminium, magnesium, or zinc. Likewise, efforts with glass injection moulding have largely failed."

Fig. 7 Views of an alumina injection moulded heart pacemaker device implanted in the human body

Applications development

Early in the evolution of MIM the aim was to convert small investment castings to injection moulding. One of the early target markets was the golf industry. That has come to fruition in a few designs. An intense effort arose around titanium and the fabrication of titanium drivers. Unfortunately, the impact properties of MIM titanium (without Hot Isostatic Pressing) are unacceptable – the early drivers shattered in a cloud of dust. Attention then turned to putters, where the time from project start to end of production using MIM was just months. One stainless steel putter went into production, consuming 66,000 MIM parts in the first year. The next year it was gone. The golf industry enters each calendar year with new and improved designs, so tool life is short. Most recently we saw a wedge produced by MIM reach the market with a wholesale price of $93 based on a fabrication cost estimated at $12.

Likewise, jewellery tends to be short term production, where rings, watches and other decorative items have short lives. Consumer decorative items produced by MIM include luggage buckles, logos and cellular telephone bodies, including rumoured zirconia frames. These also come and go quickly, causing disruptive waves in the production industry. An early example was MIM titanium sunglass frames, which made it to prototype production only to immediately go out of fashion. Similar stories are told about sporting devices, including running spikes.

On the other hand, several applications have a long-term production characteristic. These components remain in production for ten to twenty years with only minor changes. Little notice is offered, for example, to long-term implant applications such as the injection moulded alumina heart pacemaker body, an example of which is shown in Fig. 7.

Hand tools are another example, where socket wrench parts entered MIM production long ago and are still without a redesign. In the mid-1990s, MIM was qualified for medical devices such as surgical staplers. This is another clear long-wave application versus golf clubs. Indeed, several industrial components share the same characteristic of remaining in production for extended times. Certain fields also remain stable and do not require new designs every year. Examples are as follows:

- Aerospace (casting cores, inlets, nozzles, linkages)
- Medical/dental (surgical tools, brackets, implants)
- Industrial (housing, solenoids, pumps, fittings, locks).

Between short-wave production items and long-wave production opportunities are a host of intermediate-wave opportunities. These are typically five- to ten-year duration projects, associated with firearms,

automobiles and computers. Time for qualification is slow, but once the component is in production it is slow to disappear.

Note that much research is examining controlled porosity implants, often from titanium. The prior developments in MIM knee and hip replacement components is adding pores for tissue ingrowth. Other materials are attracting attention, such as nitinol (intermetallic NiTi).

Some other application ideas are disclosed in the research literature. For example, transdermal drug delivery using microminiature needle arrays relies on many repeat 10 µm pyramid features in a small device. The arrays are effective in puncturing skin for localised drug delivery. Compared to passive skin patches, the transdermal punctured skin approach exhibits ten-fold more drug delivery in the first twelve hours of treatment.

Other opportunities have uncertain time frames for implementation. For example, there are early reports of MIM used to fabricate robot parts, such as manipulators. As the population ages, home care supplemented by personal robots could greatly expand this opportunity. Heat management in electric and hybrid vehicles is a field where injection moulding is used to form heat sinks. Pictured in Fig. 8 is an example of one such device. The problem is to avoid heating the semiconductors controlling the electrical loads – semiconductors are inefficient as temperature increases. Thus, during use the control circuit must be cooled. As hybrid or electric vehicles continue to expand, more devices are needed. Although the semiconductor cooling mounts are large, at up to 200 mm in length, the geometries are ideal for injection moulding due to the multiple staggered fins and cooling channels. Similar thermal management issues are seen in internet servers and other forms of remote information storage.

Finally, future energy sources promise opportunities for Powder Injection Moulding, such as the tritium laced pellets fed into fusion reactors. Reportedly, up to 160 per

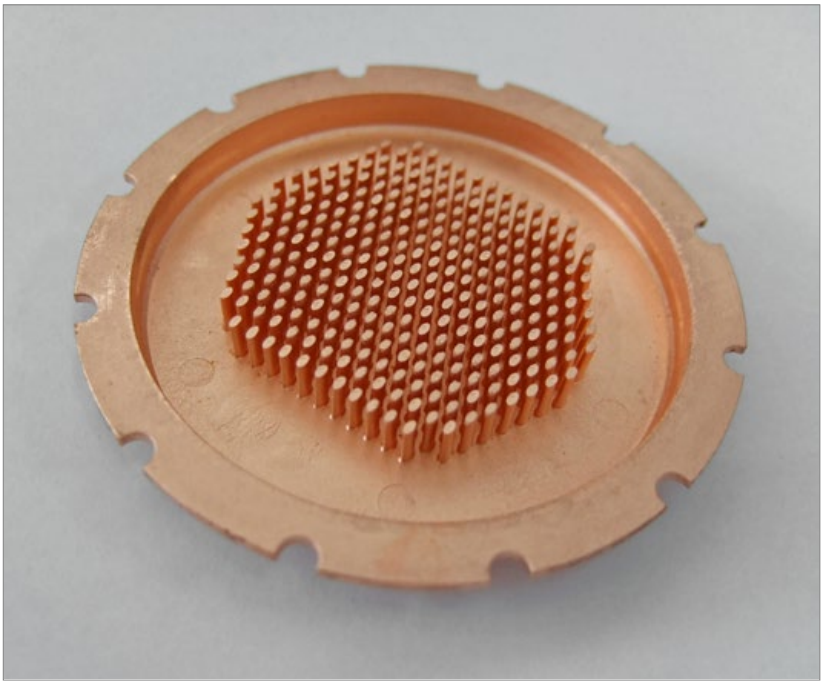

Fig. 8 A large copper heat sink made by Metal Injection Moulding for use in a hybrid automobile for cooling the control semiconductors (Courtesy Lye King Tan, Singapore Institute of Manufacturing Technology, Singapore)

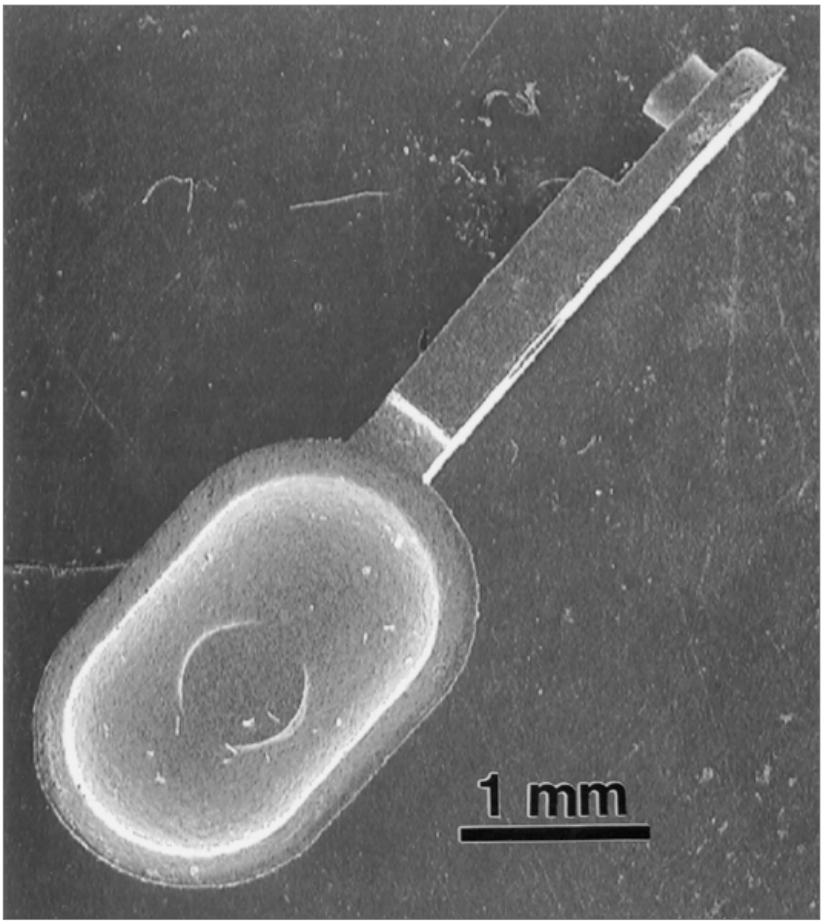

Fig. 9 This tiny biopsy piece has 100 µm wall thickness and is an example of a long-wave medical application involving microminiature moulding

Fig. 10 These tiny dental supports show the potential of Metal Injection Moulding of microminiature devices

second would be used. The problem with this opportunity is that current fusion reactor technology is still operating in a negative energy situation. It takes more energy to ignite the fusion reaction than is captured from the reactor. Should this problem be corrected, then enormous quantities of multiple layer pellets could be fabricated by MIM.

Process opportunities

The process growth opportunities are tied to economics. The first is the recognised opportunity in microminiature components. Dental orthodontic brackets and tissue biopsy jaws were some of the first successes and the latter is shown in Fig. 9. Note that today a 0.1 g stainless steel dental bracket sells for $6000/kg, while a more traditional 7 g steel trigger sells for $140/kg. As a benchmark, the US casting industry averages $33/kg in sales and Powder Metallurgy (press-sinter) averages $8.40/kg. The ability to fabricate small components adds much value. Indeed, humans seem to now value smaller things, as evidenced by so many consumer products. Fig. 10 shows an image of high-value, small dental components. But also, as illustrated in Fig. 11, there are opportunities in small features. This latter picture is a scanning electron micrograph of the cutting tips on a dental endodontic reamer for root canal procedures.

Additive Manufacturing

AM is a closely related technology that builds on the platform created by Powder Injection Moulding. Two of the technologies are extremely close to PIM – Binder Jetting and Fused Filament Fabrication. The binders are modifications of those used in injection moulding, the powders are the same, and sintering is similar. However, Additive Manufacturing approaches have advantages in avoiding tooling, so production starts sooner. Without tooling, smaller orders are cost-competitive. The sintered and heat-treated properties are similar, and in some instances slightly higher, for Additive Manufacturing thanks to better process control, since smaller furnace loads are typical.

Rapid sintering

One of the far-reaching changes taking place in sintering science is rapid sintering based on the application of a field during heating. Many variants are being explored, most derived from spark sintering ideas known for over a hundred years. Electric fields or microwave radiation are applied in conjunction with a rapid furnace heating cycle. Such cycles with a supplemental electric field allow sintering in times as short as three minutes. For example, yttria-stabilised zirconia is sintered at 900°C in a 500 V/cm electric field, versus 1400°C for equivalent sintering using traditional furnaces.

The idea for rapid sintering arose for refractory metals and ceramics, but is now documented for most metals. The productivity gain is enormous once the binder is removed; sintering is so fast one can envision coupling the rate of sintering to the rate of moulding. Binder removal, then, is the slow step. A host of ideas are emerging for ceramics, but several demonstrations have been made for fast sintering metallic components.

The challenge is to apply the electric or other field at the appropriate point in the heating cycle to jump to conditions conducive to densification. From a scientific viewpoint, the electric field avoids dwelling under conditions where detrimental surface diffusion and grain growth events occur that consume sintering potential without densification. The trials so far have focused on simple geometries. Thus, much effort is required to migrate from the early laboratory experiments to effective production arrangements. This is an ideal focus for industry-

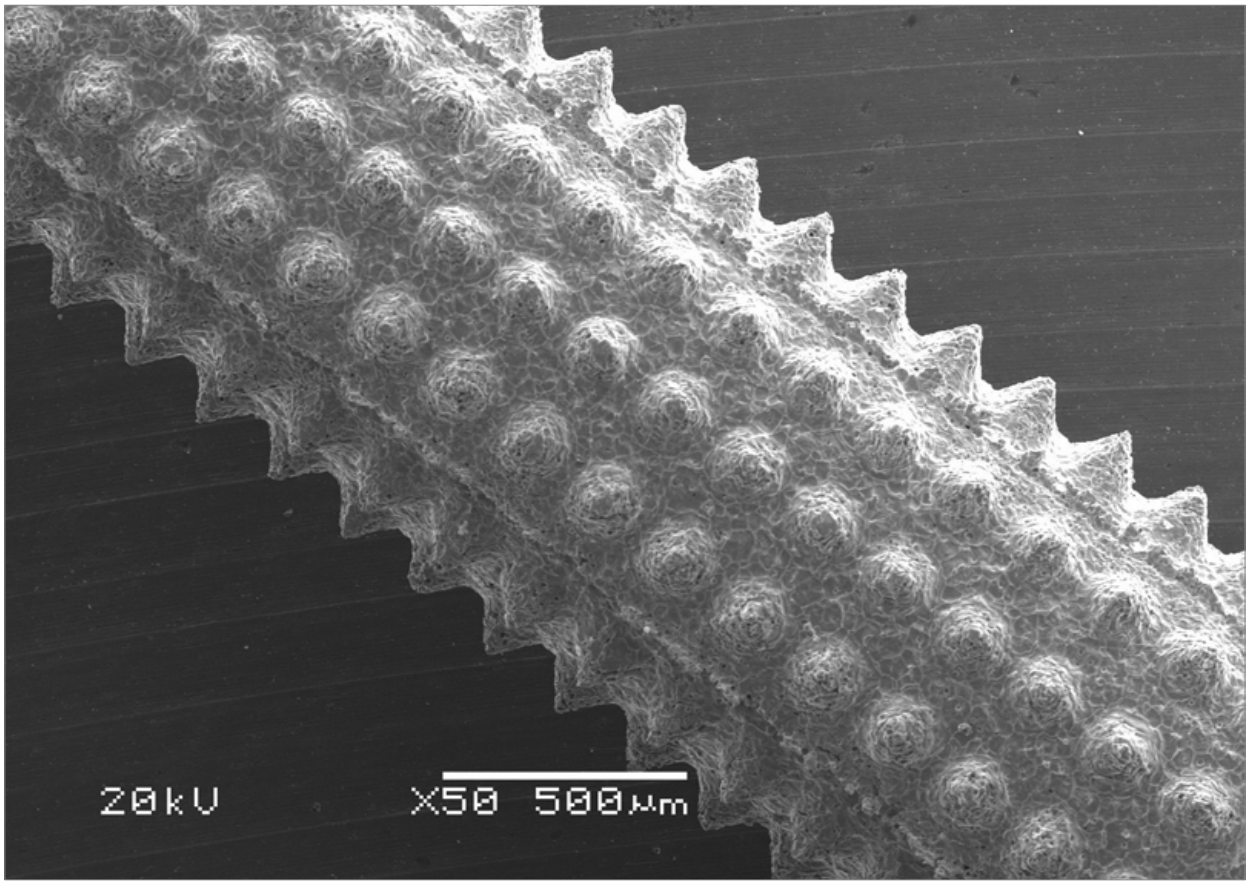

Fig. 11 A scanning electron micrograph of a dental endodontic hand tool fabricated using metal Powder Injection Moulding to place 1500 pyramidal bumps on the tapered shaft

wide research, to buy down the risk, since every production facility could eventually benefit. Unfortunately, the days of PIM industry support for independent research organisations came to an end in the middle 1990s.

Efficiency gains

The Metal Injection Moulding Association (MIMA), a constituent part of the Metal Powder Industries Federation (MPIF), conducts annual surveys on industry needs. Some of the challenges are paraphrased as follows:

1. Improve dimensional control
2. Improve process yield
3. Reduce time to market
4. Produce smaller lots
5. Integrate continuous process improvement culture
6. Improve skills

The first requires integrated sensors and adoption of closed-loop feedback control, especially at the moulding machine. Such instrumentation packages are available, but adoption is slow. The second has the same underlying theme – a need for instrumentation.

Obviously, Additive Manufacturing with the same powders and sintering cycles is a response to the third and fourth challenges. Finally, the last two challenges revert to personnel and training. If the industry were to upgrade training, integrate sensors and further embrace Additive Manufacturing, then these core challenges would be overcome. Indeed early work on Additive Manufacturing showed durable injection moulding tooling could be fabricated in five days, so reduced time to market is demonstrated, but not embraced. At times the industry seems to have a classic NIH (not invented here) philosophy that impedes progress.

"early work on Additive Manufacturing showed durable injection moulding tooling could be fabricated in five days, so reduced time to market is demonstrated, but not embraced...."

Innovations in HIP

Most sintered components have residual porosity, as is the case for castings. Hot Isostatic Pressing is applied to remove porosity in components susceptible to fatigue or impact fracture, for example medical implants, firearm components, aerospace parts and turbochargers. The scale of strength increase is small, but the fatigue life is often doubled. Traditional HIP involves long cycles, but new ideas for rapid Hot Isostatic Pressing are applied to cast turbochargers, giving many cycles per day. One variant relies on a pressure pulse generated by confined ignition of a fuel. Another variant relies on rapid transformation of a liquid to gas, such as liquid nitrogen injected into a hot chamber containing preheated components. Both are effectively forging the powder compact. Cost is reduced by the increased number of consolidation runs per day. More outstanding are the mechanical property gains. A 50% strength increase is possible in steels. Further, it is realised that pressure alters the time-temperature-transformation behaviour for a steel, delaying transformations and enabling higher mechanical properties. The option for in-line serial HIP emerges from the forging type treatments developed for automotive turbochargers.

Key points on growth

Management theory says a good manager is probably only correct 55% of the time. Several options are outlined above for how the Powder Injection Moulding industry might drive future growth. Some of the predictions are fairly safe, such as pointing out how Additive Manufacturing is both a competitive option and a complementary option. The competitive aspect arises since AM relies on the same powder-sintering rules and often involves similar binders, without long debinding. The layer-by-layer build using solvent additions to the binder enables pore perforation without the need for first stage debinding. The solvent evaporates on each layer, giving pores for final binder removal during sintering. In other words, for limited production quantities, say below 10,000 per year, Binder Jet AM without debinding is faster and cheaper. Early reports show about three-fold faster furnace runs in MIM furnaces when the pores are open, since slow binder removal steps are not required.

This report focuses on three areas where growth is possible. New materials, and the advent of higher melting temperature structural materials are the key directions. Titanium aluminides are offered as an example. Such materials require processing sophistication, but once mastered provide a long-running opportunity. New applications should align with longer-duration products, getting away from the 'fashion industry' that makes up so much of PIM.

Applications in smartphones, home appliances, exercise monitors and other devices sometimes land with a splash but within months are gone. On the other hand, long-duration products are seen in aerospace, medical and industrial fields that can have production runs lasting twenty years.

The golf industry by comparison changes designs every year, making for short, intense production, but little residue. The ranking of application fields from most stable to least stable is as follows:

1. Aerospace (cores, inlets, nozzles, linkages)
2. Medical/dental (surgical tools, brackets)
3. Industrial (pumps, housing, fittings, locks)
4. Firearms (triggers, guards, spindles)
5. Automotive (turbochargers, rocker arms)
6. Computers (hinges, connectors, heat sinks)
7. Communications (cell phone hinge, vibrator)
8. Consumer (arrowheads, luggage, logos)
9. Jewellery (watches, rings, cufflinks).

The last growth opportunity is from improved processes. Automation and closed-loop control are options that will improve current practices, and new technologies such as fast sintering, rapid HIP (isostatic forging) and Additive Manufacturing are obvious means to improve product quality.

Several sources of further information are attached to help guide the reader to more details. It is characteristic that the science is about twenty years ahead of industrial success. Ponder that the first patents in PIM were filed in the 1940s, but it took another fifty years to become viable. Thus, we find the platforms for most of these opportunities to grow Powder Injection Moulding are known. The task ahead is to implement around these opportunities.

Acknowledgement

Uwe Haupt of Arburg GmbH & Co KG, Germany, initially requested my thoughts on the future of the industry be presented at the company's user meeting last June in Lossburg. Based on many requests for a copy of that talk those notes were organised for this article.

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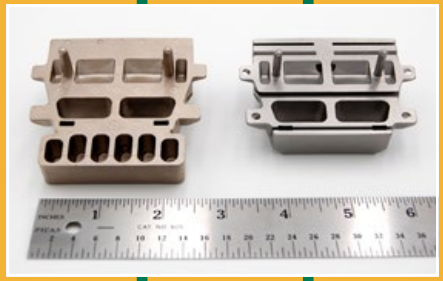

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The Metal Injection Moulding of tungsten and its alloys: A review

In this article Jiupeng Song, Wei Wang, Binyou Yan and Xiangcao Jiang review recent developments in the MIM of tungsten (W), oxide dispersion strengthened tungsten (ODS-W), tungsten rhenium (W-Re), tungsten copper (W-Cu) and tungsten heavy alloys (WHAs). The production methods for MIM-grade powders with good flowability and sinterability are presented and the effects of powder characteristics, sintering and Hot Isostactic Pressing (HIP) process parameters on density and microstructure for W and ODS-W are summarised. For liquid phase sintering of W-Cu and WHAs, the powder type and sintering profiles, which are critical for material properties and surface conditions, are also discussed.

Tungsten and its alloys such as oxide dispersion strengthened tungsten (ODS-W), tungsten rhenium (W-Re), tungsten copper (W-Cu), tungsten heavy alloys (WHAs), etc, are widely used for various applications thanks to the properties of high melting point, high density, high thermal conductivity and low coefficient of thermal expansion. These materials fall into two groups according to the types of sintering, the first including W, ODS-W and W-Re, which are densified by solid state sintering, and the second consisting of W-Cu and WHAs, which are liquid phase sintered. Due to the poor machinability of these materials, MIM is considered a cost-effective route to mass-produce parts with complex geometries [1, 2].

MIM W, ODS-W or W-Re have a very high melting temperature above 2500°C, and are generally used for electrodes in arc discharge lamps [3], plasma-facing components in fusion devices [4-6] and cathodes in ion sources [7]. Porous W skeletons can also be made via MIM and a more homogeneous microstructure can be obtained, attributed to the hydrostatic pressure during injection compared to die pressing. Subsequently, electronic emission materials or liquid metal propellants are infiltrated into the interconnected pores [8, 9]. W-25 wt.%Re, a type of solid-solution strengthened alloy, has excellent high-temperature mechanical properties. A MIM W-25wt.%Re rocker nozzle throat has recently been investigated [10].

MIM W-Cu and WHAs are composites densified via liquid phase sintering. W-Cu is an

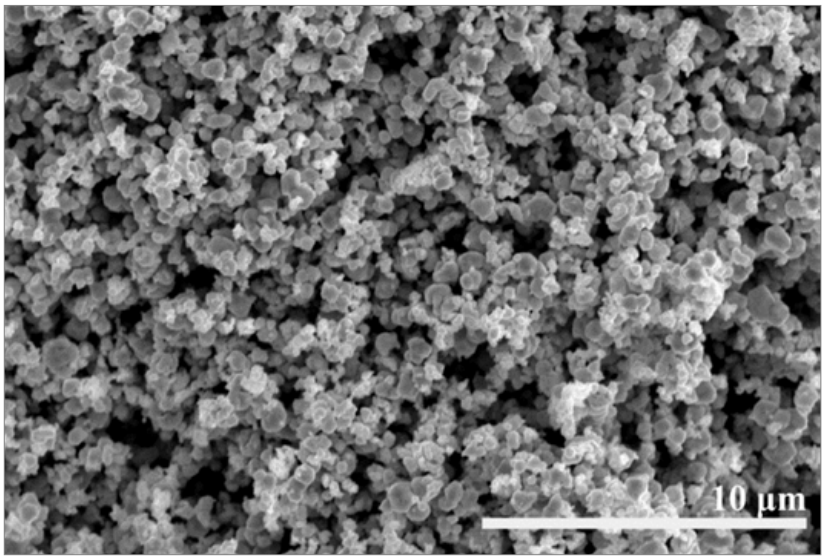

Fig. 1 Deagglomerated W powders used in the experiments with a particle size of FSSS 0.7 μm

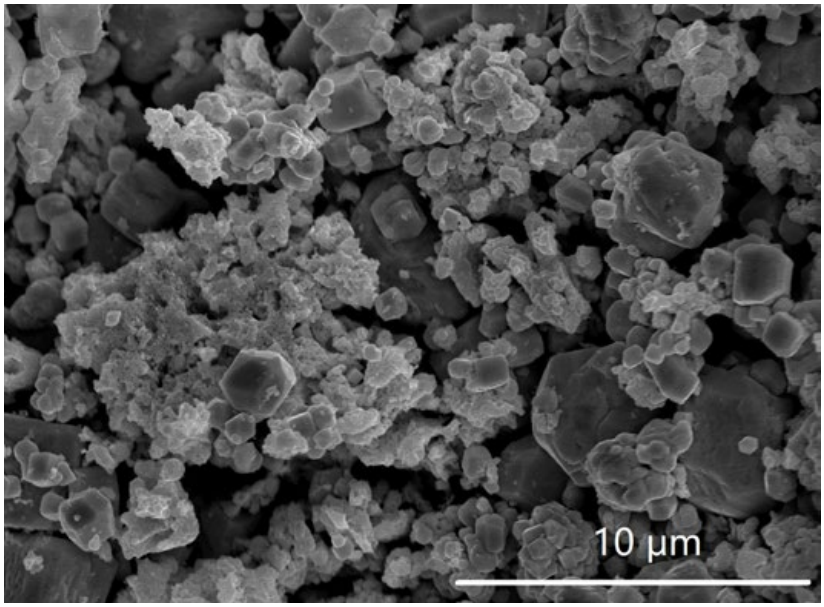

Fig. 2 W-1 vol.% Y_2O_3 powder produced by liquid-liquid doping

attractive thermal management material for power electronics due to the combination of high thermal conductivity of Cu and low coefficient of thermal expansion (CTE) of W [11, 12]. Various efforts have been carried out to improve the sinterablity of W-Cu powder for MIM. Another application is the use of MIM to produce W-Cu shape charge liners for oil and gas industries [13]. MIM WHAs (e.g., W-Ni-Fe, W-Ni-Cu) components are widely used as weight balances in electronic devices or warhead parts for the military [2, 14].

Powder preparation

W powder

In order to reach high densities, fine W powders with good sinterability are employed for MIM. The strong agglomeration of fine W powders, however, makes their flowability very poor, which significantly decreases the solid loading of the feedstock. Milling operations are often used for deagglomeration, which can effectively reduce the mixing torque during feedstock preparation [15, 16]. A type of deagglomerated ultrafine MIM W powder with the Fisher Sub Sieve Sizer (FSSS) particle size of 0.7 µm (Fig. 1) can be mixed with a standard wax-based binder to form a feedstock with solid loading of 51 vol.% [7]. Mixing the W powders with different particle sizes is an alternative to improve the flowability (e.g., FSSS 0.7 µm + FSSS 1.7 µm) [4].

The powder for WHAs is generally deaggolomerated W powder and the other elemental powders, for example Ni, Fe or Cu.

ODS-W powder

Wet or dry doping can be used to produce ODS-W powder. Ball milling (i.e., solid-solid doping) is a simple way to mix W and La_2O_3 or Y_2O_3 powder [5]. In industry, solid-liquid doping is widely used by spraying lanthanum nitride solution onto the tungsten oxide powder. The powder is then reduced in a hydrogen atmosphere where the salt is pyrolysed, forming a fine and dispersed oxide phase. It seems that the wet doped powder has a more homogeneous distribution of oxide. Recently, liquid-liquid doping has been employed to produce ODS molybdenum (Mo) by blending the solution of Mo salts and lanthanum nitride. The liquid blend is subsequently spray dried, calcinated and reduced. With this innovative process, a nanostructured ODS-Mo is obtained with most La_2O_3 nano particles distributed

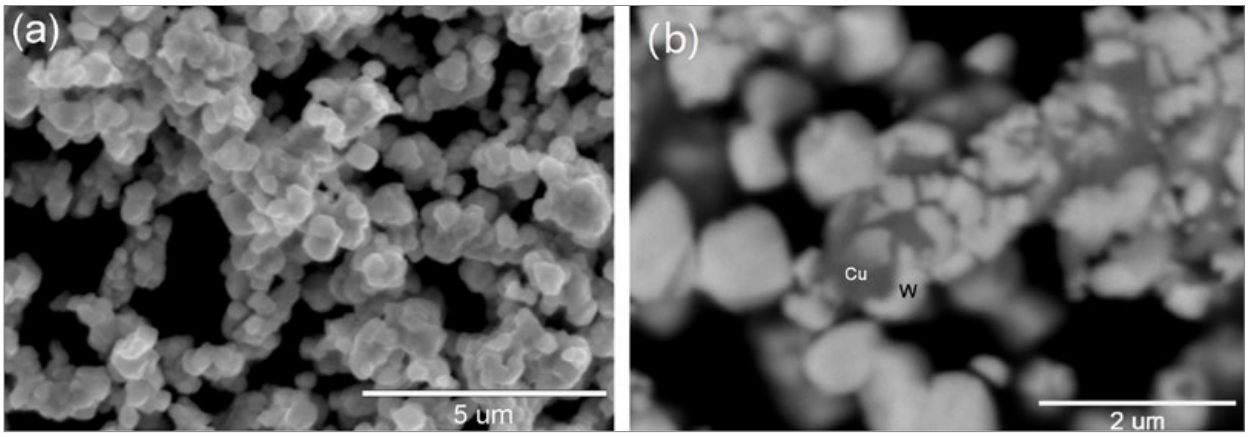

Fig. 3 SEM images of W-10 wt.% Cu ultrafine composite powders showing (a) surface morphology and (b) cross section

inside the Mo grains. Both strength and ductility of this type of ODS-W improve significantly [17]. The same route can be applied for ODS-W [18]. A type of W-1 vol.%Y_2O_3 powder produced by liquid-liquid doping is shown in Fig. 2.

W-Cu ultrafine powder

The sintering of mixed W-Cu powder to reach high density is difficult because W and Cu are not mutually soluble, especially for the low Cu content condition. Ultrafine or nanostructured W-Cu composite powder is an alternative which offers a solution to these problems. Various methods such as ball milling, mechanical alloying, oxide co-reduction, mechano-chemical process and thermo-chemical process have been used to fabricate ultrafine W-Cu composite powder [19-25]. The characteristics of ultrafine W-Cu composite powders with Cu content of 10, 15, 20 and 25 wt.% fabricated from W and Cu salts by thermo-chemical process are shown in Table 1 [13]. Fig. 3(a) is an example of the morphology for W-10 wt.%Cu ultrafine composite powder. The distribution of W and Cu in the composite powder cannot be identified directly from Scanning Electronic Microscopy (SEM) images. However, Energy-Dispersive X-ray Spectroscopy (EDX) analysis shows that, inside one particle, both W and Cu elements exist, which means that the distribution of W and Cu is homogeneous in the scale of an agglomerated particle. A cross section of the composite powder (Fig. 3(b)) shows the distribution of W and Cu in the particles.

		W-10Cu	W-15Cu	W-20Cu	W-25Cu
Particle size distribution	D10 (μm)	1.54	1.52	2.32	1.60
	D50 (μm)	3.78	3.92	4.82	4.35
	D90 (μm)	18.93	7.33	9.82	12.08
Specific surface area (m^2/g)		0.72	0.89	0.99	0.92
Apparent density (g/cm^3)		1.75	1.64	1.37	1.22
Tap density (g/cm^3)		3.48	2.91	2.50	2.21
FSSS (μm)		0.98	0.43	0.71	0.89
Theoretical density (g/cm^3)		17.28	16.42	15.64	14.93

Table 1 Characteristics of W-Cu ultrafine composite powder

The MIM process

MIM process for W and its alloys includes feedstock preparation, injection moulding, debinding, sintering and Hot Isotactic Pressing if necessary, which is similar to MIM for other materials. A wax-based binder is generally used, which is debound by solvent and thermal methods [26, 27]. Sintering is the most critical step in obtaining the desired properties and dimensional accuracy.

Solid state sintering and HIP treatment

The fine powders of W, ODS-W and W-Re are used for MIM, but the densification to near fully dense during sintering remains a challenge. The relative density of a MIM W cathode with ultrafine W powder (FSSS 0.7 μm) was 98.4% after sintering at 1900°C for 2 h [7]. By increasing the sintering temperature to 2300°C and holding for 7 h, the density can be improved to 99.2%. However, significant grain growth occurs (Fig. 4) and the sintered part becomes very brittle.

HIP is employed as a post-sintering treatment to reach high density while controlling the grain size. An optimised sintering profile and HIP process parameters are

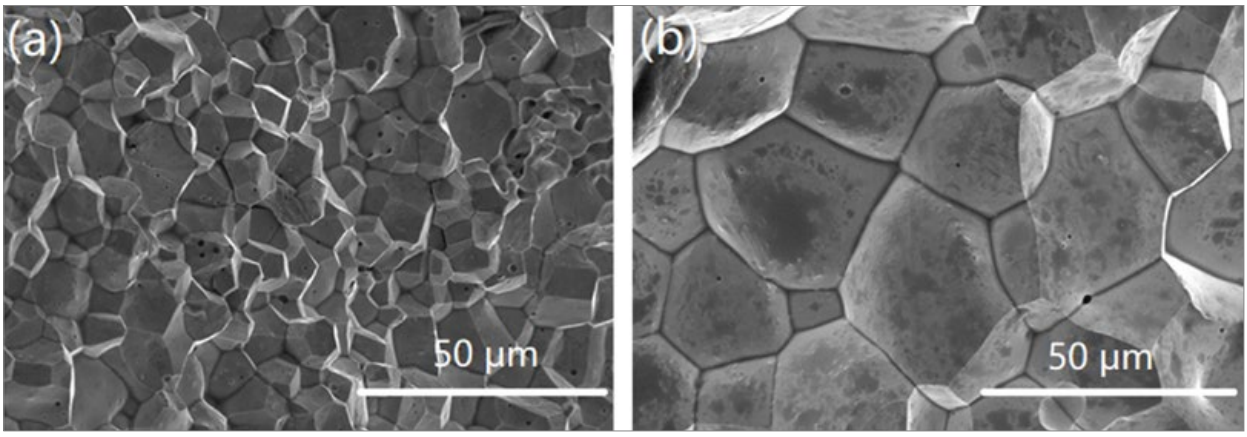

Fig. 4 The microstructures of MIM W with different sintering profiles: (a) 1900°C, 3 h and (b) 2300°C, 7 h

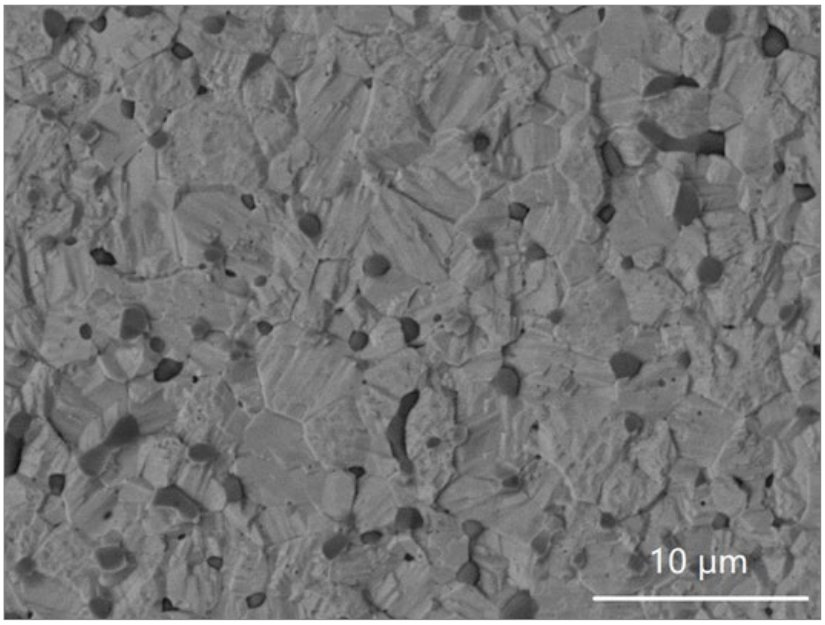

Fig. 5 Microstructure of MIM W - 1.2 wt.% Y_2O_3

critical for the density, microstructure and properties of MIM W, ODS-W and W-Re. A brief summary of previous studies is shown in Table 2. It can be seen that sintering at a relatively low temperature followed by HIP treatment is favourable for controlling the density and grain structure. In addition, La_2O_3 or Y_2O_3 particles distributed at W grain boundaries can inhibit W grain growth effectively.

Liquid phase sintering

MIM W-Cu and WHAs are densified by liquid phase sintering. Besides the material properties, the control of dimensional accuracy and surface condition are important for the purpose of near-net shaping. Oversintering results in the liquid phase extruding to the surface and the distortion of the parts. An example of a MIM W-20 wt.%Cu shape charge liner used for oil penetration is presented to illustrate the effect of powder on densification, as shown in Fig. 6. A blend of FSSS 20 µm or 0.7 µm W powder and FSSS 10 µm electrolytic Cu powder respectively, with a V-shape mixer and a type of ultrafine W-20 wt.%Cu composite powder (Table 1), were used with the same solid loading for the MIM feedstock. The sintering was carried out at 1300°C for 2 h under a H_2 atmosphere. The parts using the mechanically mixed powder had the surfaces covered with the extruded Cu, as shown in Fig. 6(b) and (c). The sintered relative density was close to 99% for the part using ultrafine composite powder (Fig. 6(d)). This can

Materials	W Powder	Sintering	HIP	Density	Grain size	Hardness
W [7]	FSSS 0.7 µm	1900°C, 2 h	no	98.4%	10-20 µm	433 HV0.1
W [5]	50% FSSS 0.7 µm + 50% FSSS 1.7 µm	1800°C, 2 h	2100°C, 250 MPa, 3 h	98.6-99%	3-7 µm	457 HV0.1
W [28]	FSSS 0.7 µm	1650°C, 2 h	1500°C, 280 MPa, 2 h	98%	5.5 µm	/
W [29]	FSSS 1-2 µm	>2000°C, 2 h	1500°C, >300 MPa,	97.4-98%	10-20 µm	357 HV10
W [30]	FSSS 0.7 µm	1700°C, 2 h	1700°C, 180 MPa, 1 h	98.5%	10-15µm	403 HV30
W-2 wt.%La_2O_3 [5]	90% FSSS 0.7 µm + 10 % FSSS 1.7 µm	1800°C, 2 h	2100°C, 250 MPa, 3 h	96.5-97.2%	3 µm	586 HV0.1
W-2 wt.%Y_2O_3 [5]	90 % FSSS 0.7 µm + 10 % FSSS 1.7 µm	1800°C, 2 h	2100°C, 250 MPa, 3 h	96.3-97.1%	3 µm	617 HV0.1
W-0.26wt.%Y_2O_3 [29]	FSSS 1-2 µm	>2000°C, 2 h	1500°C, >300 MPa	97.0-98.1%	3-10 µm	400 HV10
W-1.36wt.%Y_2O_3 [29]	FSSS 1-2 µm	>2000°C, 2 h	1500°C, >300 MPa	95.5-95.9%	2-7 µm	457 HV10
W-1.2wt.%Y_2O_3 [30]	FSSS 0.7µm	19500°C, 4 h	no	95.3%	3-5 µm	450 HV30
W-1.2wt.%Y_2O_3 [30]	FSSS 0.7µm	1700°C, 2 h	1700°C, 170 MPa, 1 h	95.9%	3-5 µm	447 HV30
Note: Theoretical density = 19.25 g/cm^3						

Table 2 Sintering and HIP treatment of MIM W and ODS-W

be attributed to the strong capillary force among the fine W particles, which can hold the liquid phase Cu during the sintering of ultrafine W-Cu composite powder [12,13]. The homogeneous microstructure of sintered MIM W-20 wt.% Cu composite powder is shown in Fig. 7.

Various papers have presented investigations on the sintering of MIM WHAs. Adequate liquid phase sintering is important for the mechanical properties of the parts, such as vibrator weights in consumer electronics (Fig. 8) and prefabricated fragments used in warheads (Fig. 9). However, oversintering can cause an unacceptable surface condition with extruded liquid phase, which often occurs at the roots of the bosses or protrusions in MIM parts (Fig. 10). The corresponding optical microscopic image (etched) is shown in Fig. 11.

Conclusions

The powder characteristics of W, ODS-W, W-Re and W-Cu are critical for MIM. The proper powder has adequate flowability for preparing a feedstock with a high solid loading. On the other hand, the powder should have good sinterability to reach a high sintered density.

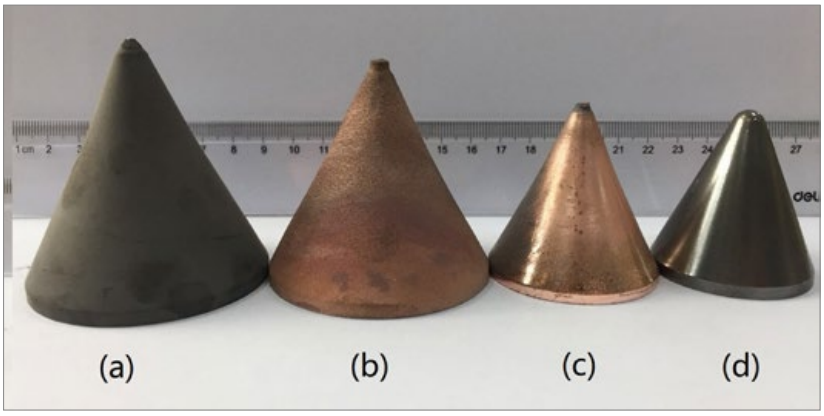

Fig. 6 MIM W-20 wt.% Cu shaped charge liners (a) injection moulded, (b) sintered using the mixture of FSSS 20 μm W powder and FSSS 10 μm electrolytic Cu powder, (c) sintered using the mixture of FSSS 0.7 μm W powder and FSSS 10 μm electrolytic Cu powder and (d) sintered with FSSS 0.7 μm W-20Cu composite powder

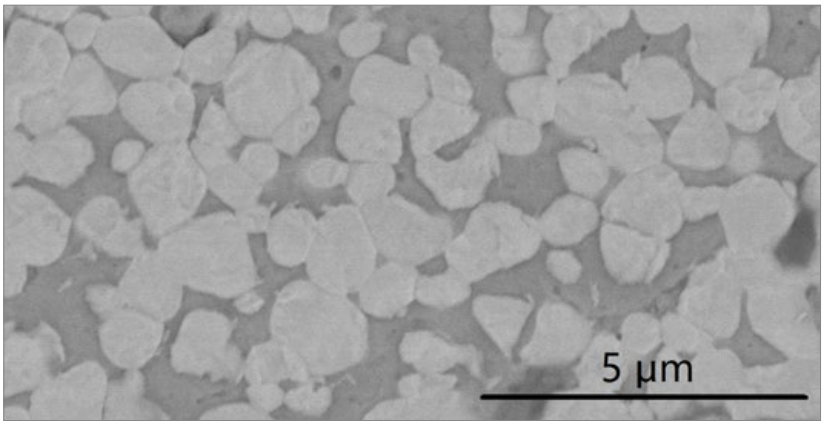

Fig. 7 SEM image of sintered MIM W-20 wt.%Cu with FSSS 0.7 μm composite powder

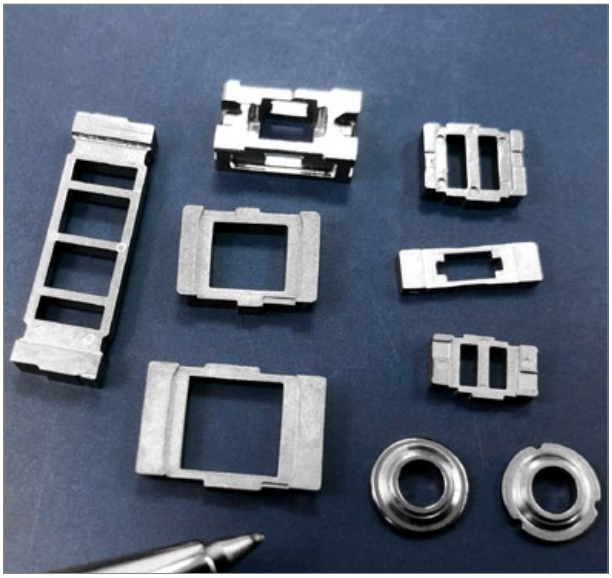

Fig. 8 MIM WHA vibrator weights in consumer electronics

Fig. 9 MIM WHA prefabricated fragments

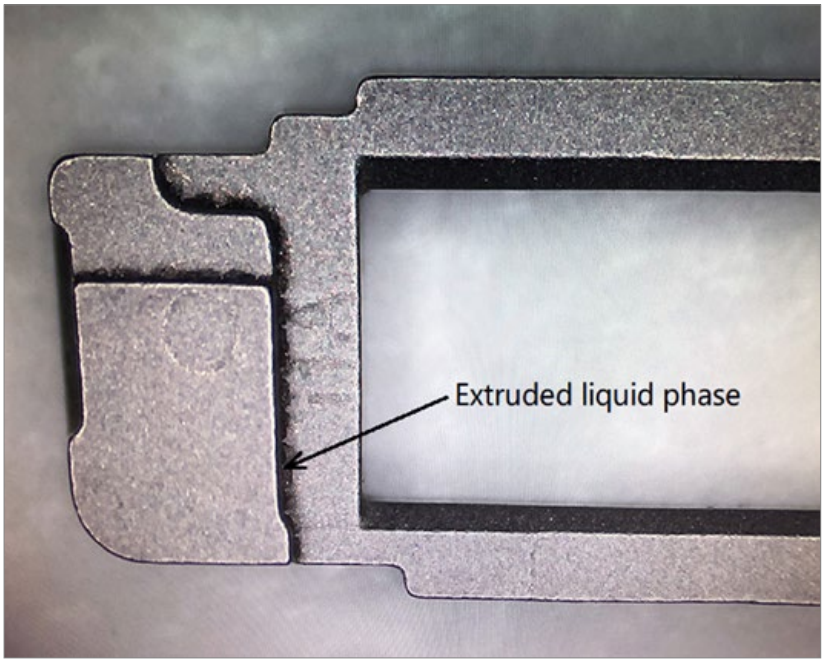

Fig. 10 Liquid phase extruded to the surface during the sintering of MIM WHA parts

For solid state sintering for W, ODS-W and W-Re MIM parts, HIP treatment is employed for near full densification. The optimised process parameters of sintering and HIP are important for density and grain structure. For liquid phase sintering for W-Cu and WHAs, proper sintering should be carried out to obtain MIM parts with both good mechanical properties and surface conditions.

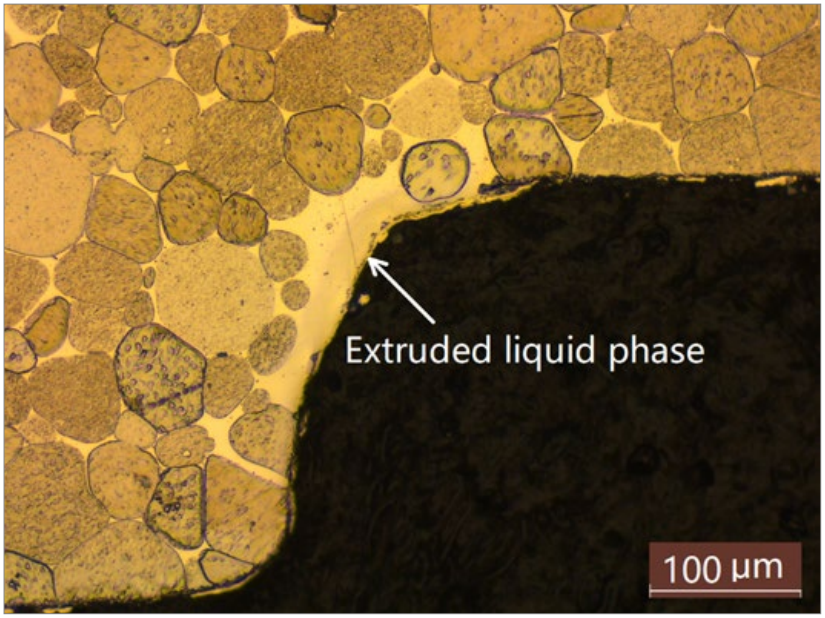

Fig. 11 Optical microscopic image of the local area of the part in Fig. 10 showing an extruded liquid phase

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Regloplas variothermal temperature controls and hot runners: Expanding the capabilities of PIM technology

When developing its groundbreaking smartphone frame solutions, Arburg GmbH & Co KG turned to technology from Switzerland's Regloplas AG in order to enable the moulding of large, high-aspect ratio parts that would have been impossible to produce with conventional mould temperature controls. In this article, Regloplas' Siegfried Hohlbaum introduces the technologies used in the project and explains how they can be efficiently applied in a MIM production environment.

In 2016, Arburg GmbH & Co KG, Lossburg, Germany, first revealed its MIM smartphone frame demonstrator, drawing headlines with this high-profile example of how PIM technology could drive cost-savings and innovation in a new generation of smartphones. In the development of the project, Arburg relied on Switzerland's Regloplas AG for a customised injection moulding solution, based on variothermal temperature control technology, in order to produce large, high-quality parts requiring only minimal reprocessing. The resulting system simultaneously offers a very short return on investment and simple operation.

Whilst conventionally Powder Injection Moulding has been used for the production of small and complex-shaped metal and ceramic parts, for some years a trend has been visible towards the production of larger parts with higher aspect ratios. This development is reflected in market interest in the production of smartphone frames by Metal Injection Moulding.

Isothermal versus variothermal moulding

Until now, Powder Injection Moulding processes have typically relied on an isothermal mould temperature to produce parts. Since this temperature is considerably lower than the melting point of the feed material, which has a high thermal conductivity, high injection speeds are required. Without these higher speeds, adequate filling of the cavities cannot be achieved without the premature freezing of the feed material. However, an increased injection speed usually leads to differences in density and the green parts produced by this method therefore often have an inhomogeneous density distribution.

Fig. 1 Left: two P180M units, one each for heating and cooling. Right: the Vario switching unit and energyBattery

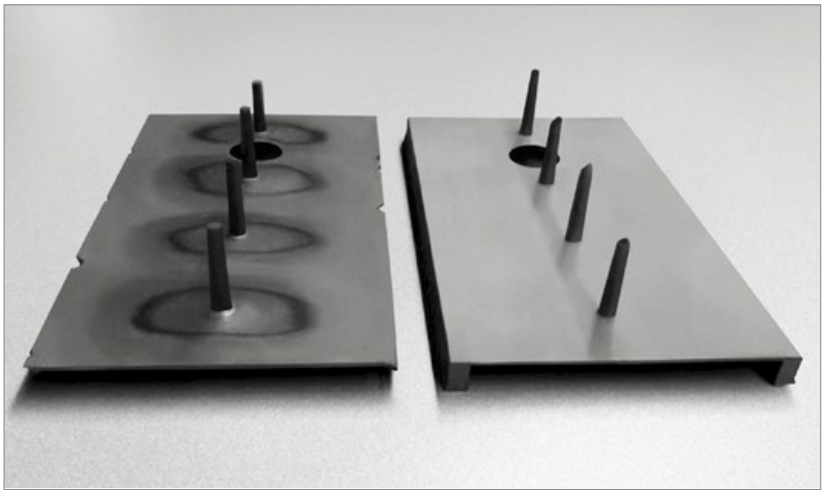

Fig. 2 Green parts with isothermal tempering (left) and with variothermal tempering (right) by Regloplas show striking differences in quality (Courtesy Arburg GmbH + Co KG)

Fig. 3 Sintered and polished smartphone frames showing the high surface quality that can be acheived (Courtesy Arburg GmbH + Co KG)

This inhomogeneity also results in significant distortion during sintering. Depending on the feedstock material, dark-coloured segregation lines may appear around the injection point and along the flow paths. In order to avoid these deficiencies in the part, the mould temperature must be brought to the melting point in a controlled manner during injection.

Variothermal temperature control is the basis for dynamic mould temperature control. By switching between defined temperatures, the user can directly influence the surface moulding and the solidification behaviour of the feedstock; a variothermal temperature control unit has two temperature control circuits with different temperature levels, and switching between these circuits allows for targeted heating or cooling. This process creates an individual temperature delta in the mould.

Case study: Smartphone frame

In the Metal Injection Moulding of smartphone frames, long flow paths and thin wall thicknesses must be achieved simultaneously. In addition, the segregation lines that typically result from this type of application must be eliminated. The feedstock used in this study was Catamold 316 LG Plus stainless steel.

In the early stages of the project to optimise the moulding of the smartphone frame, it became clear that the key to success would be to perfectly coordinate the interaction between the mould, the hot runner system and the dynamic mould temperature control system through the use of variothermal temperature control with an 'energyBattery' from Regloplas. Arburg, together with MIM feedstock specialist BASF SE, had developed a mould that featured temperature channels close to the cavity. This enabled the necessary rapid heating and cooling, a basic requirement for effective variothermal temperature control, known as dynamic mould temperature control.

Variothermal temperature control is vital in order to simultaneously achieve long flow paths with a constant green density and thin wall sections. Regloplas calculated the key data for the temperature levels of 120°C and 170°C based on the component geometry and the intended feedstock. The first trials were carried out with a P180M/18/SM73H/SK-RT100 temperature control unit for heating and a P180M/8/SM73H/SK- RT100 type device for cooling, supplemented with the Vario switching unit plus energyBattery (Fig. 1).

A further advantage of variothermal temperature control was identified during the use of these systems, which is shown in Fig. 2. The moulded part on the left was produced using isothermal mould temperature control. Due to the thin wall sections, the available injection pressure (2500 bar) of the injection moulding machine was insufficient to fill the part completely. This resulted in unacceptable segregation lines.

The part on the right of Fig. 2 was produced using variothermal temperature control technology from Regloplas. The part was completely filled at injection pressures below 600 bar and shows no segregation lines or other disruptive factors. The surface

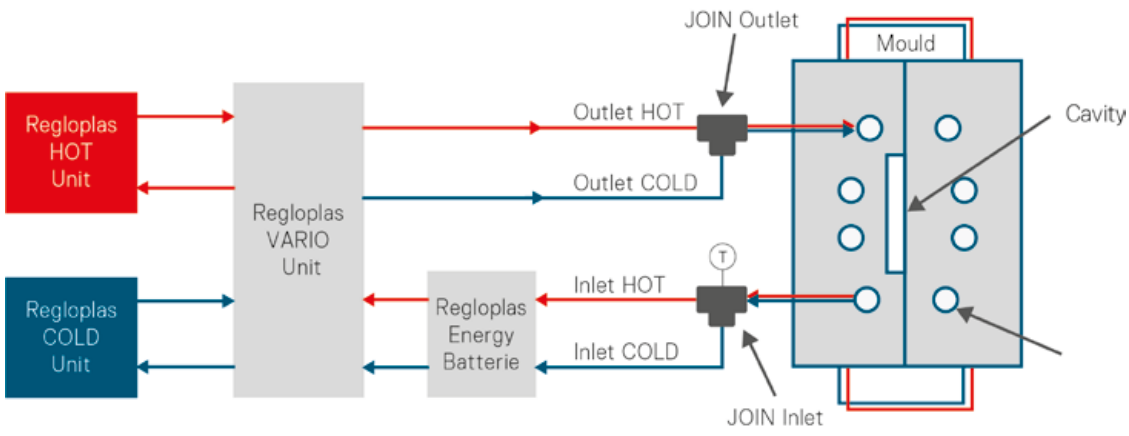

Fig. 4 Schematic diagram of a mould temperature control system with the energyBattery

appearance is extremely uniform and the segregation lines around the sprue that are typical of isothermal mould temperature control were completely eliminated. After sintering, the surface of the parts appears highly uniform and no visible defects can be seen. This is a great advantage for parts used in visible applications in a product, as they require less polishing work.

Process enhancement with energyBattery

The rapid change between hot and cold water at temperature levels of 120°C and 170°C causes tremendous pressure changes and stress on the material in the temperature control unit. By using an energyBattery, Regloplas has minimised temperature deviation, reducing the problem of pressure strokes, and increased process stability.

The energyBattery serves as a storage unit for the liquid used in the process at the required temperature. By switching between the two temperature levels in the Vario switching unit, the stored liquid can be returned to the process circuit quickly – and without additional energy expenditure – by using the Regloplas energyBattery.

The dynamic mould temperature control requires a total power consumption of 32 kW. Thanks to the energyBattery, this application resulted in an energy saving of approx. 2.3 kW (see the schematic diagram of the energy battery in Fig. 4). This leads to monetary savings of between €2,700–5,400 per year, calculated assuming a machine utilisation level of 89.3% over 24 hours/seven days a week and an electricity price of €0.15–0.30 per KWh. As a result, a return on investment can be achieved within the first year of operation, depending on the type of energy battery and the electricity price.

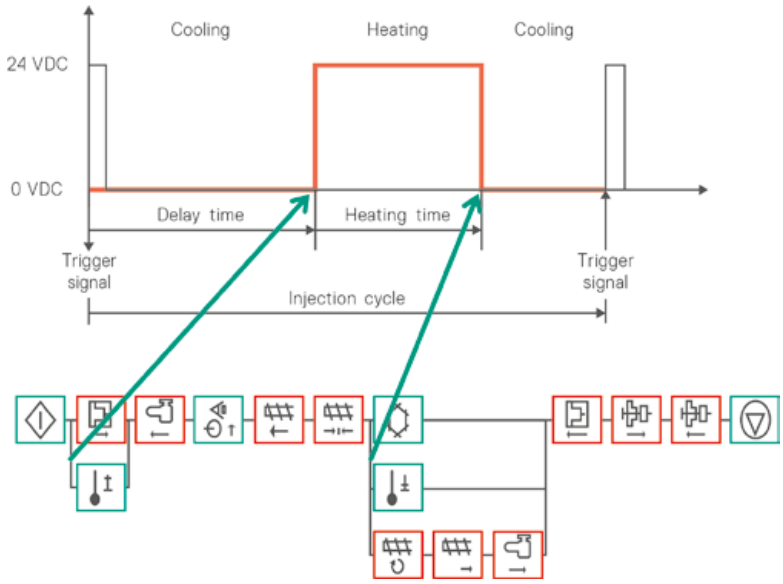

Fig. 5 Visualisation of the process sequence

Communication with the machine control system

Regloplas also developed and programmed a special interface between the Vario switching unit, the energyBattery and the machine control system for communication with the injection moulding machine. This interface means the operator can operate the system easily and design the work process flexibly. Thanks to the integration of process signals into the machine control system, the desired process parameters are easily programmed and the preset temperatures continuously monitored.

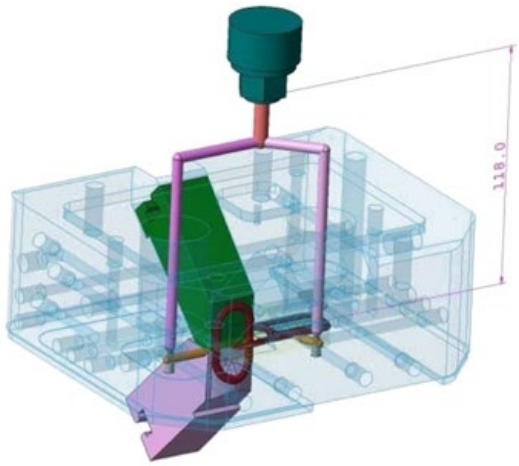

Fig. 6 A 3D drawing of the hot runner system for the key fob (Courtesy Arburg GmbH + Co KG)

Fig. 7 The Regloplas 200Smart temperature control unit

Regloplas also recommended the installation of additional remote access to the Vario switching unit. Direct access for measurements, data acquisition and other functions was therefore available via laptop or equivalent device. Fig. 5 shows schematically the switching cycles of the temperature levels in connection with the visualised process sequence of the Powder Injection Moulding process.

Case study: Key fobs

In a second project, Arburg cooperated with Regloplas on a PIM key fob development project in which a focus was on the challenge of shortening the sprue runner in the moulding of both metals and ceramics. In the Regloplas Vario system, particularly in Metal Injection Moulding, a hot runner is required in combination with the Regloplas 200Smart temperature control unit.

There is currently a noticeable trend towards multiple cavities in Powder Injection Moulding production. When it comes to incorporating multiple cavities in a PIM tool, it is essential that the route of the runner to each cavity is of equal length. The sprue runner must therefore be branched accordingly. To guarantee this parameter, Arburg opted for a temperature-controlled liquid hot runner. The solution developed by Regloplas resulted in high-quality green parts with excellent process stability.

The challenge

For multiple cavities, the hot runner had to be set up for several slides with sprue runner lengths of more than 13 cm (see Fig. 6). The challenge here is to place the hot runner as close as possible to the multiple cavities, despite the very limited space available. This enables the cold runners to be significantly shortened.

The challenge with multiple cavities is that the feedstock needs to be evenly temperature-controlled. It must not be allowed to overheat at any time, as this will result in a degradation of the feedstock. Stable temperature control, however, cannot be sufficiently guaranteed using electric hot runners. Therefore, temperature control free of fluctuations was achieved using a Regloplas temperature control unit operating with oil.

An increased injection rate can also often lead to density differences in the green parts being produced, and this lack of homogeneity in the density generates strong warpage during sintering. Depending on the feedstock, separations occur around the injection point and along the flow path. To avoid these shortcomings, the tool temperature must be brought to melting temperature at the point of injection.

At the same time, the feedstock requires stable and very precise temperature controlling of the hot runner, which heats the runner area separately from the tool. This keeps the feedstock in the runner area permanently free-flowing, preventing

premature freezing. In addition to this, it allows longer flow paths to be created, since the compound first begins to cool in the cavity.

An optimised hot runner, operated using a temperature control system that is free of fluctuations, should therefore allow the Powder Injection Moulding of runners and parts with long flow paths with minimal tolerances and thin wall thicknesses in multiple cavities.

In order to achieve this target, Arburg shared with Regloplas the necessary mould data, end-product data and the technical specifications of the materials. This generated an initial, customer-specific temperature control calculation from which it was possible to calculate and design the desired hot runner. Regloplas also supported Arburg on-site with the test run, fine tuning of the parameters and measurement of the final production values.

The BASF feedstock used has a viscosity that is extremely temperature-dependent. In order to guarantee that the final product was of the highest possible quality, a constant feedstock viscosity was required. It was therefore essential that the hot runner with the temperature-controlled medium delivered the best possible temperature constancy.

A temperature control unit was developed for Arburg that could fulfil its specifications of a maximum temperature deviation in the control unit of +/- 0.3 K. Using the 200Smart, which was developed specifically for the project (Fig. 7), the first test runs of the hot runner could be carried out.

For the first trials, a test mould for manufacturing the key fob was developed. Green parts with various differing shapes are shown in Fig. 8. The sprue and runner lengths are 1.3 and 2.3 cm. The mould was specifically set up for the Regloplas 200Smart temperature-controlled liquid hot runner.

Using this temperature-controlled liquid hot runner and the specially developed oil temperature control unit, the Regloplas 200Smart enables a constant input temperature with deviations of less than +/- 0.3 K. This

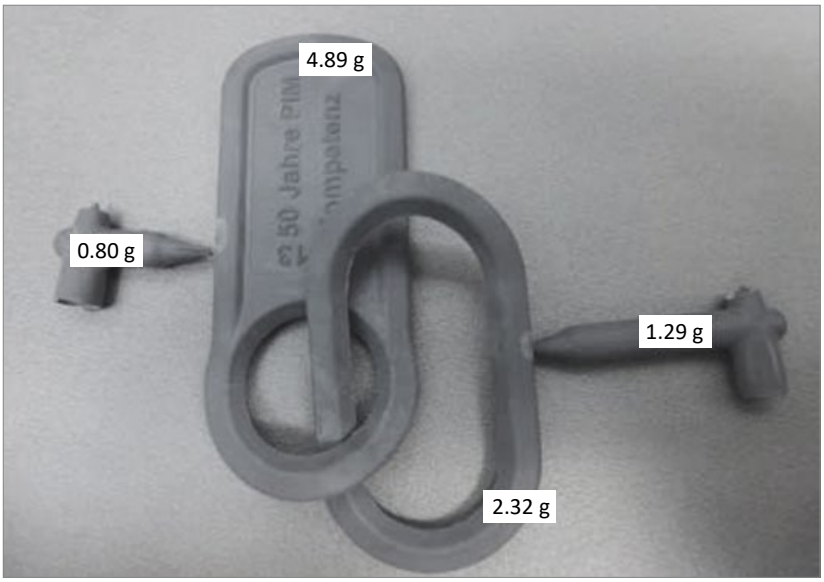

Fig. 8 Green parts showing the weight of the two components and their sprues (Courtesy Arburg GmbH + Co KG)

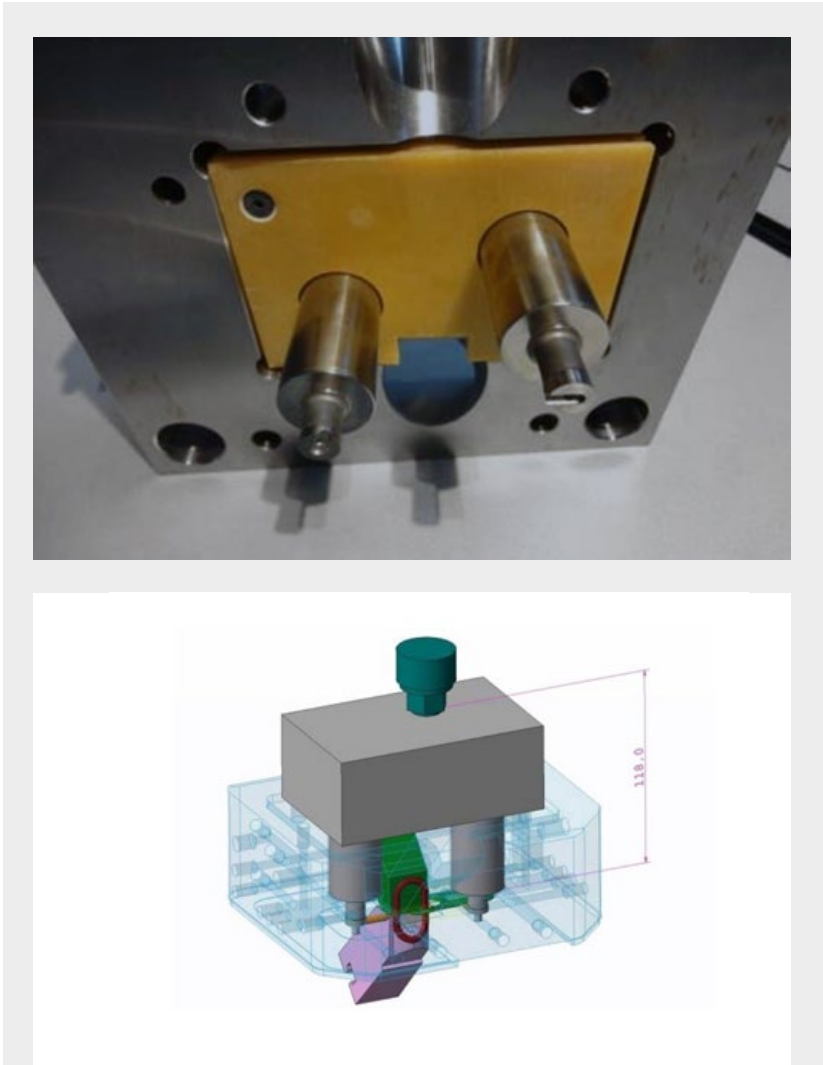

Fig. 9 A temperature-controlled fluid hot runner system for the key fob (Courtesy Arburg GmbH + Co KG)

Fig. 10 The finished key fob components (Courtesy Arburg GmbH + Co KG)

guaranteed effective control of the flowability of the feedstock. Fig. 9 shows the hot runner system for the production of the key fob.

Summary

With its variothermal temperature control, Regloplas offers the PIM industry a user-friendly solution for the production of sophisticated, thin-walled and complex components. As demonstrated in the development of the smartphone frame, the use of variothermal temperature control eliminates segregation effects when using Catamold 316 LG Plus feedstock, resulting in a uniform surface quality. At the same time, constant pressure distribution is achieved in the component and thus a constant green density.

In parallel, the use of the Regloplas energyBattery ensures energy savings with excellent process stability and thereby reduces the cost of ownership for production. The integration of process signals into the machine control system allows for simple and direct adaptation of the desired process parameters as well as the monitoring of preset temperatures.

The technology enables the production of parts with homogeneous surfaces with a cycle time of less than one minute when using an appropriately designed mould, with the ability to mould long flow paths at a constant green density. Additionally, the injection moulding machine requires a significantly lower clamping force and can therefore be more compact, resulting in a lower purchase price, lower operating costs and overall reduced cost of ownership in production.

Ultimately, as PIM parts become larger and ever more complex, this system guarantees the highest possible part quality of the final product, with maximum reproducibility.

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PMCC EXPO

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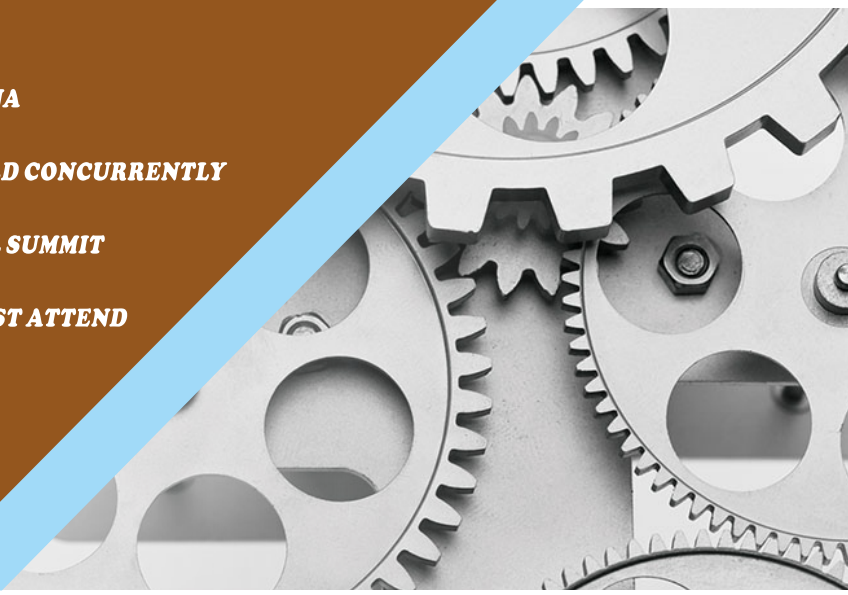

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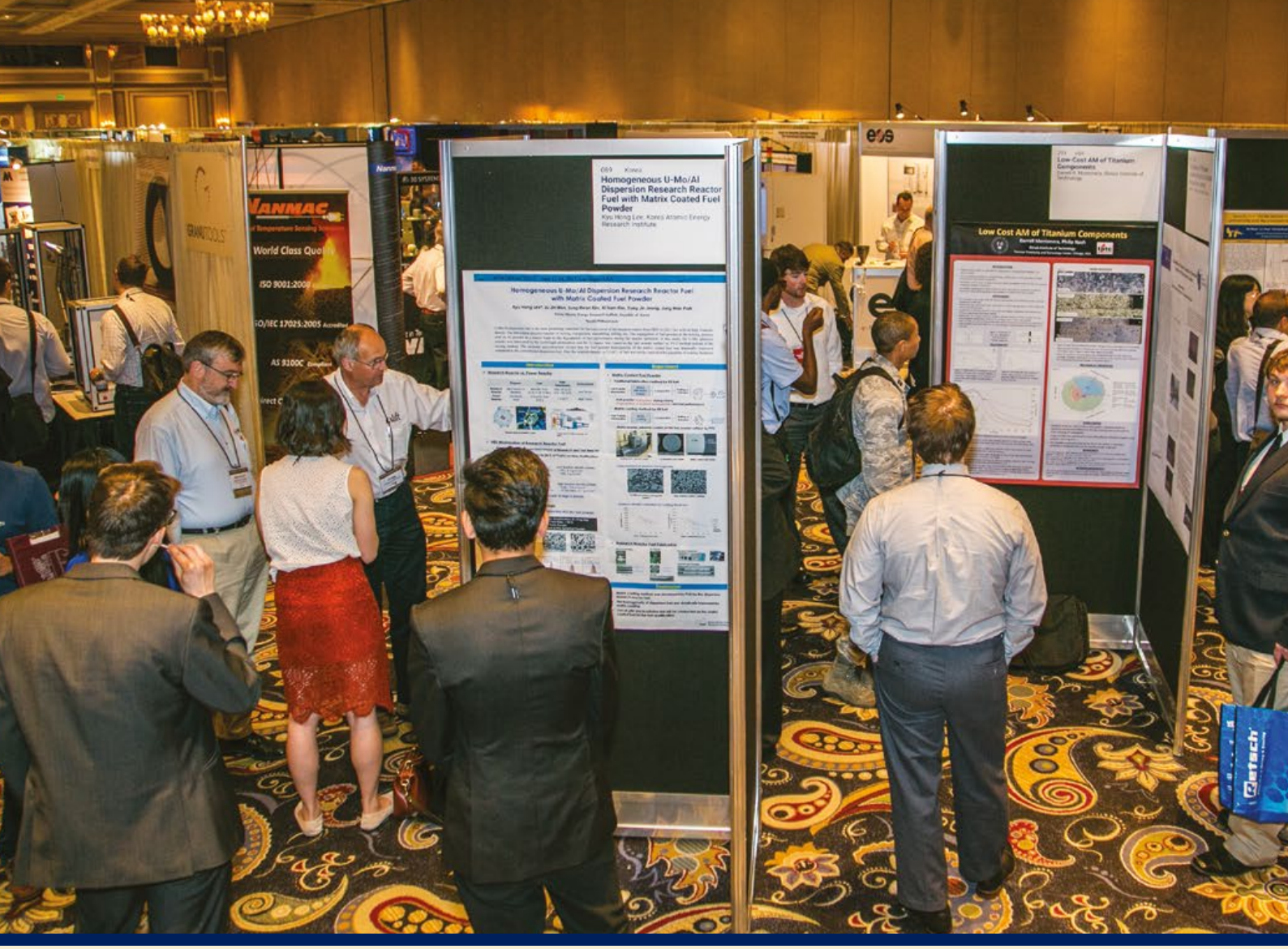

WORLDPM2018 Beijing: Technical sessions highlight advances in MIM stainless steels

Powder Injection Moulding was one of the key themes at the WORLDPM2018 Congress held in Beijing, China, September 16-20, 2018. The processing of stainless steels, as well as new and novel stainless steel applications, were highlighted in a number of technical presentations. In this special report from Beijing, Bernard Williams, Consulting Editor, reviews a selection of these papers.

The global Powder Metallurgy community gathered in Beijing, September 16-20, 2018, to attend the first World PM Congress and Exhibition to be held in China to date. This successful event was organised by the Chinese Society for Metals and the China Powder Metallurgy Alliance, with more than a thousand delegates from forty countries in attendance. The WORLDPM2018 Congress featured nearly four hundred presentations, Special Interest Sessions - including a session covering the market status of Powder Injection Moulding - a number of plenary reports, an international display of poster papers, and a large exhibition featuring the latest advances from global powder producers and equipment suppliers.

This article reviews four PIM presentations from Beijing which focused on novel stainless steel applications as well as on advances in the cost-efficient production of fine MIM-grade powders, and for an improved grade powder giving excellent surface finish in sintered MIM stainless steel parts.

MIM parts used in laptop computers

Metal Injection Moulding is increasingly being used in consumer electronics/3C applications, especially for small, lightweight components having complex shapes which would be more expensive to produce by conventional manufacturing processes such as stamping, forging and machining. Huang Yunbin and Jiang Ronggao, Shanghai Jingke Powder Metallurgy Technology Co Ltd, Kunshan Town, Songjiang District, Shanghai, China, shared insight during their presentation into how laptop computers use a number of parts made by MIM including hinges, parts used on shafts such as concave-convex wheels, retainer plates, bearing frames/housings and gear seats, to name a few [1]. The main materials used to produce these MIM parts include stainless steels 316L, 304L, 17-4 PH, 420 and 440, Fe-2Ni, Fe4Ni, Fe8Ni, and Fe-Ni soft magnetic materials.

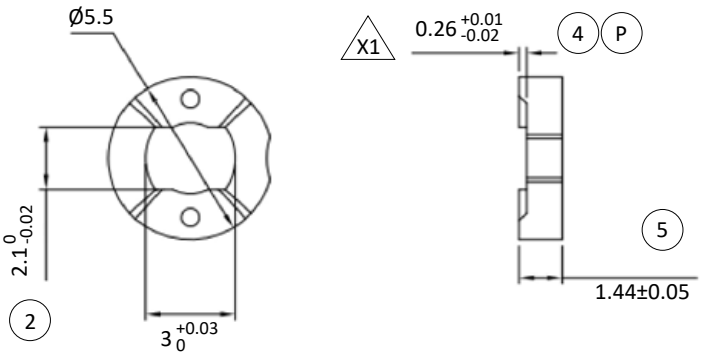

Fig. 1 Schematic of the MIM shaft cam [1]

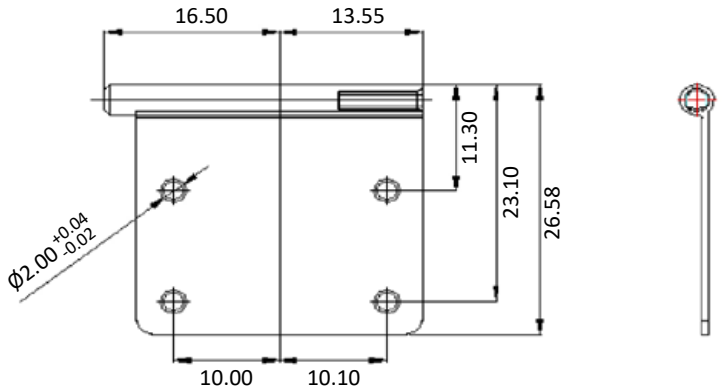

Fig. 2 Schematic of the shaft fixing plate [1]

Material	Hardness (HRC)	Tensile strength (MPa)	Breaking force (kgf)
Fe8Ni	45–52	≥ 1000	≥ 18
17-4 PH stainless steel	35–41	≥ 850	≥ 18

Table 1 Performance requirements for the MIM grade Fe8Ni and 17-4 PH stainless steel in laptop applications [1]

Performance	1	2	3	4	5
Surface roughness (Ra)	0.8—1.6				
Density (g/cm^3)	7.60	7.55	7.58	7.61	7.59
Hardness (HRC)	48	48	49	51	50
Tensile strength (MPa)	1210	1180	1230	1220	1195
Breaking force (kgf)	32	31	32	29	33

Table 2 Data obtained from performance tests on the MIM Fe8Ni material [1]

Performance	1	2	3	4	5
Surface roughness (Ra)	0.8—1.6				
Density (g/cm^3)	7.66	7.65	7.60	7.65	7.67
Hardness (HRC)	37	38	40	36	38
Tensile strength (MPa)	870	886	885	879	875
Breaking force (kgf)	28	27	27	26	28

Table 3 Data obtained from performance tests on the MIM 17-4 PH stainless steel [1]

The authors stated that MIM parts have gained acceptance because of their good mechanical properties (strength, toughness and hardness), good dimensional accuracy and good surface finish (≤ 1.6 μm).

The authors gave examples in their presentation of two MIM parts in actual production at their company. The first was a shaft cam (Fig. 1) made from an Fe8Ni alloy powder (composition: Fe-8Ni-0.5Mo-0.66%C), and the second a shaft fixing plate (Fig. 2) produced from a 17-4 PH stainless steel powder. The performance requirements for the two MIM materials are shown in Table 1. The dimensional accuracy required in the final parts for both materials is ±0.3–0.5%.

The shaft cam shown in Fig. 1 is paired with another product's concave wheel. Combined, they produce a counter grinding so as to allow control of the angle of flip of the top casing of the laptop computer. The cam is formed in an eight cavity mould with an injection moulding cycle of around 16 s, giving a daily production rate (over 22 h) of 39,600 pieces. After moulding the binder is removed by solvent extraction using alcohol, followed by thermal debinding and vacuum sintering at 1250°C for 90 min. The sintered parts are quenched, blasted, plated and tempered before final inspection.

The shaft fixing plate (Fig. 2) is used as a shaft structure support, so that when the flip cover of the laptop reaches a certain angle (greater than 90°) the cover plate is supported. The shaft fixing plate is produced from a 17-4 PH stainless steel grade by moulding in a two cavity mould with a cycle time around 30 s. Daily (22 h) output is 5,200 pieces. The feedstock for this MIM part uses a plastic binder based on polyoxymethylene with catalytic debinding done using nitric acid. This is followed by thermal debinding and partial pressure sintering at 1275°C with 2 h holding time at temperature. The sintered parts are subjected to solid solution and aging heat treatment, magnetic grinding, mirror polishing and PVD coating before final inspection.

The authors undertook five performance tests for both the Fe8Ni and 17-4 PH MIM parts, and the results of these tests are shown in Tables 2 and 3. Dimensional accuracy was also found to fully meet customer requirements.

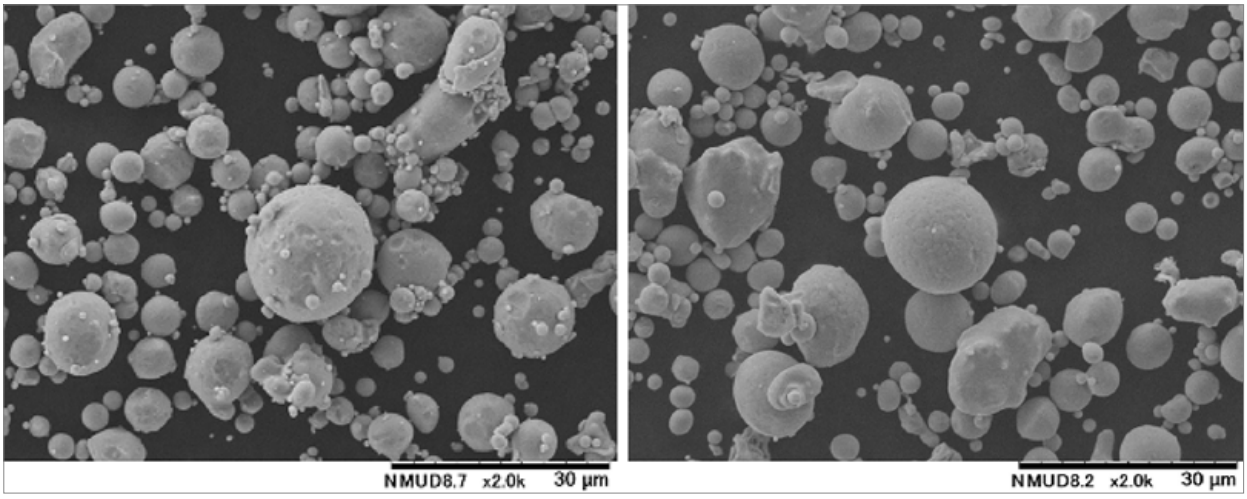

Fig. 3 SEM images of the water atomised 316 stainless steel powders; (left) comparison powder; (right) new development powder [2]

Water atomised stainless steel powder for MIM parts with excellent surface properties

Austenitic stainless steel 316 and precipitation hardening stainless steel 17-4 PH are two of the key materials used today to produce MIM components for applications in mobile phones because of their good mechanical properties and corrosion resistance. However, inadequate final properties such as low sintered density and oxide impurities can lead to unacceptable surfaces including pin holes and corrosion in the MIM parts. Masaki Mori and co-authors at Mitsubishi Steel Mfg. Co Ltd, Kawahigashi-machi, Aizu-Wakamatsu, Japan, reported on the development of a new grade of 316 stainless steel (Fe-11Ni-17Cr-2Mo) produced by water atomisation which they claim can be sintered to higher density and having a lower final oxygen content [2]. The 316 powder was found to give an excellent surface finish with metallic lustre in sintered MIM parts when compared to a standard 316 grade water atomised stainless steel powder. The authors state that the new 316 powder shows good potential for applications such as MIM smartphone cases and also for other consumer electronic components where a good surface finish is required.

The study reported on by the authors involved the comparison of the new grade 316 stainless powder and a standard 316 grade. Both were produced by water atomisation and SEM images of the two powders are shown in Fig. 3. D50 particle size distribution is 9.2 µm and 9.1 µm for the comparison and newly-developed powders, respectively. However, whilst the oxygen contents in both powders were similar at 0.361% and 0.328%, the carbon content in the newly-developed powder was higher at 0.190% compared with 0.028% in the comparison 316 stainless steel powder. The authors stated that the reason for the higher carbon content is to promote the carbon-oxygen reaction during sintering, and thereby reduce the oxygen to 0.075% in the final sintered parts. This compares with 0.288% oxygen content in the sintered parts made from the comparison powder as can be seen in Fig. 4.

The two 316 grade powders were blended with a special binder and kneaded for 2 h in a planetary mixer at a powder to binder ratio 93.5:6.5 by weight to produce the MIM feedstock. The moulded and debound parts were then sintered at 1573 K, 1598 K, 1623 K and 1648 K under partial

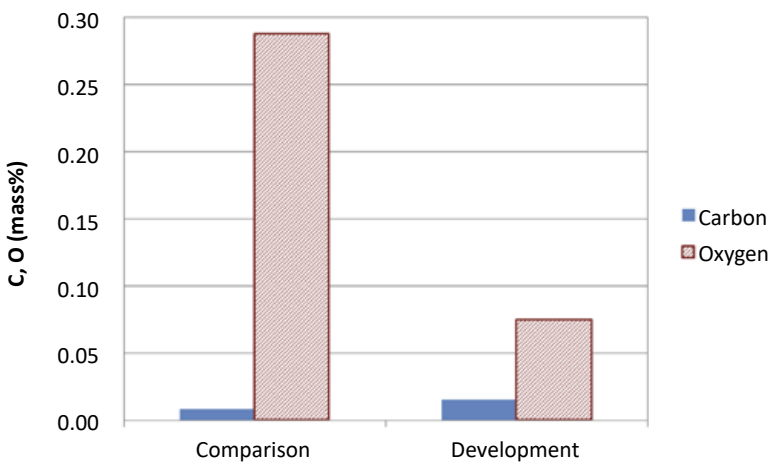

Fig. 4 Carbon and oxygen contents of MIM 316 parts sintered at 1648 K [2]

	Sintered density (g/cm³)			
	Top temperature × 2.5 h			
	1573 K	1598 K	1623 K	1648 K
Comparison	7.61	7.62	7.66	7.80
Development	7.52	7.54	7.63	7.85

Table 4 Sintered densities of the MIM 316 parts at different high temperatures [2]

pressure in argon for 2.5 h, and their sintered densities were determined as shown in Table 4. As can be seen, the sintered density in the comparison 316 powder was higher at up to 1623 K, reaching 7.66 g/cm³. However, at the highest temperature of 1648 K it was the newly-developed powder which was highest at 7.85 g/cm³. This was attributed by the authors to the fact that volume transport is more active than surface transport at the high sintering temperature (1623 K to 1648 K), so that the gas generated by the carbon-oxygen reaction was discharged to the outside of the sintered body resulting in both higher density and lower oxygen content.

In terms of the excellent surface finish claimed by the authors in the sintered MIM parts, they reported that there is no apparent difference between the newly-developed 316 stainless steel powder and the comparison powder when looked at with the naked eye. However, there is a marked difference in the surface finish when looked at under the microscope (Fig. 5).

Comparing the rheological properties and dimensional accuracy of 17-4 PH feedstock using water and gas atomised powders

Indo-MIM Pvt. Ltd., based in Bangalore, India, is one of the world leaders in manufacturing complex-shape and high-precision MIM components, weighing from 0.1 to 200 g, for the automotive, consumer electronics, industrial, aerospace and medical sectors. The company has manufacturing operations in India and the USA.

Feedstock design and the characteristics of the powders and binder systems used can greatly influence the rheological properties and deformation during sintering in MIM. B N Mukund and T S Shivashankar reported on their research to measure the feedstock rheology of one of the key MIM materials – 17-4 PH stainless steel – using both fine, spherical gas atomised powder and irregular-shaped fine water atomised powders [3]. The gas and water atomised powders had different particle size distributions, varying in mean particle size from finer to coarser (3 µm to 20 µm). The authors focused on correlating the powder particle parameters in relation to feedstock viscosity – shear rate, shear sensitivity, mouldability during injection and deformation during sintering. The characteristics of the four chosen 17-4 PH gas and water atomised powder grades used in the study are shown in Table 5.

In order to study the effect of powder particle size distribution and shape of the four powder types on rheological properties, MIM feedstock was produced using a binder composed of a 50:50 mixture of paraffin wax (PW, Polyaid G101, Gujarat waxes, density 0.91 g/m³, melting point 59°C) and HDPE (H2105, Huntsman, density 0.96 g/cm³, melting point 130°C). A 50 vol.% powder loading was used in all the feedstocks for the comparison of flow behaviour whereas optimal loading was derived for each

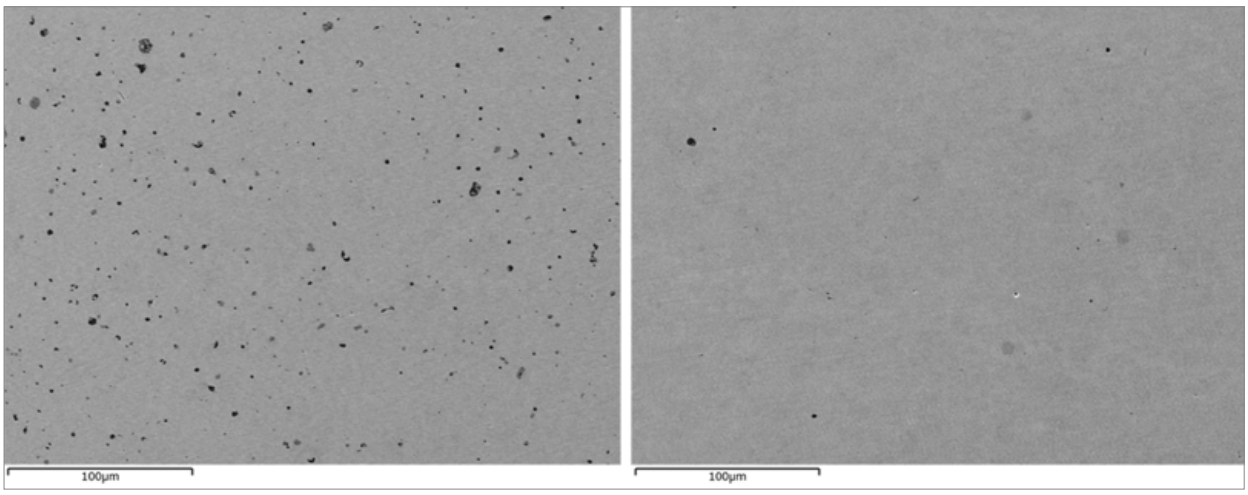

Fig. 5 SEM showing the high density and good surface finish in the MIM part produced from the new water atomised 316 stainless steel (right) and the comparison 316 powder (left) [2]

Mean particle size, D50 (µm)		Specific Surface area (m^2/g)		Pycnometer density (g/cm^3)		Tap density (g/cm^3)	
Gas	Water	Gas	Water	Gas	Water	Gas	Water
3	3	0.53	0.40	7.80	7.71	4.1	3.9
8	7	0.31	0.36	7.78	7.68	4.3	4.2
10	10	0.23	0.34	7.85	7.66	4.6	4.2
20	20	0.15	0.22	7.88	7.71	4.8	4.1

Table 5 Characteristics of 17-4 PH stainless steel powders produced by gas and water atomisation [3]

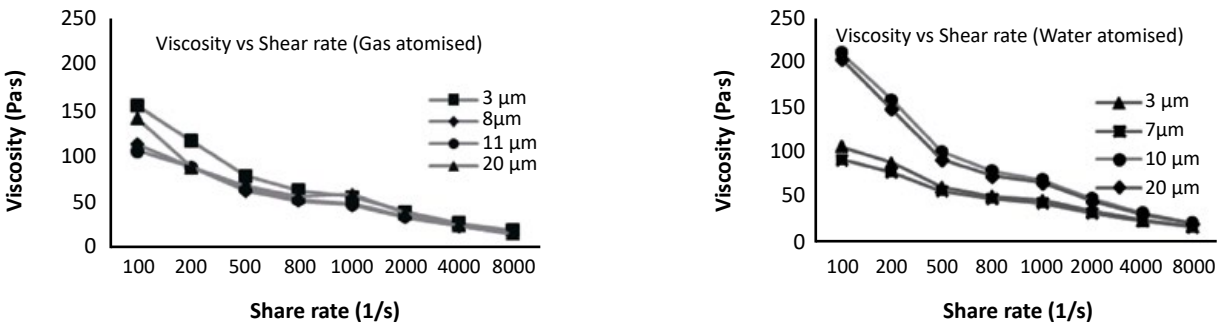

Fig. 6 Viscosity vs shear rate (l/s) of 17-4 PH powders (left: gas atomised 17-4 PH powder; right: water atomised 17-4 PH powder) [3]

chosen powder based on the torque rheology to study injection moulding behaviour and sintering deformation characteristics.

The authors used a capillary rheometer to measure the viscosity and shear sensitivity index ('n') of the feedstock. The capillary die used has L/D ratio of 10:1. The shear rates ranging from 100-8000 s^{-1} were applied and the feedstocks were tested at 180°C. The pressure drop across the die was recorded for calculating the shear stress at the die wall. The results of the tests for viscosity vs shear rate for the four different gas and water atomised feedstocks are shown in Fig. 6. The authors found that powder particle size distribution and the shape greatly influences the viscosity of feedstock. In the case of gas atomised powder, which is spherical in shape, viscosity increases with a decrease in particle size, due to the higher surface area and greater particle interaction. However, feedstock containing water atomised powder, which is irregular in shape, was found to have a higher viscosity with an increase in particle size, which again increases the surface area due to the surface irregularity, with more friction between the particles leading to powder-binder separation during injection moulding. Based on the optimal rheological properties and the cost of the feedstock formulations studied, three different powders were chosen for further injection moulding and sintering deformation studies. The gas and water atomised 17-4 PH powder chosen has a mean particle size of 7-8 µm and the spherical gas atomised powder has a mean particle size of 10 µm. The authors used an injection moulding machine of 80/210 tonnage to mould the complex shaped MIM component shown in Fig. 7. The component weighs 40 g and has a width and length of 24 mm and 40 mm respectively. The nozzle temperature was set at 180°C with an injection speed and packing pressure of 50 cm^3/s and 500 bar up to 2.5 s respectively. The component was filled at the initial filling of 50% (of total weight of the part) in the injection phase in both the chosen feedstock formulations. The remaining unfilled portion of the part was filled in a packing phase

Fig. 7 Complex MIM component used to determine level of distortion for gas and water atomised 17-4 PH feedstock [3]

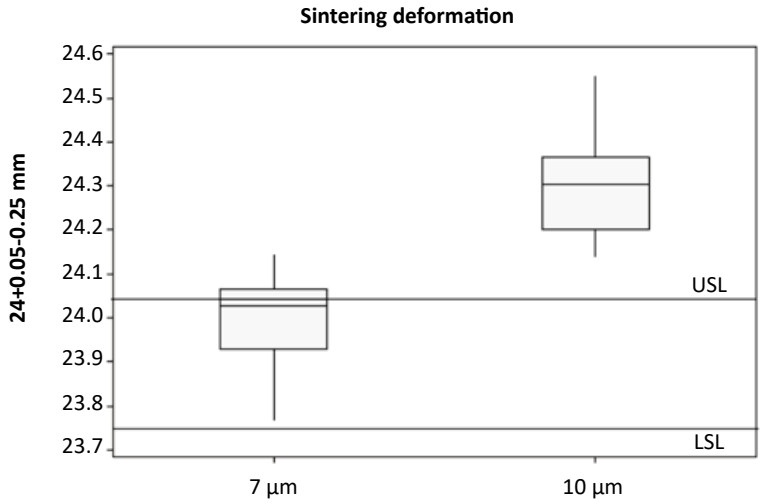

Fig. 8 Distortion measurements between 7 µm and 10 µm atomised powders chosen [3]

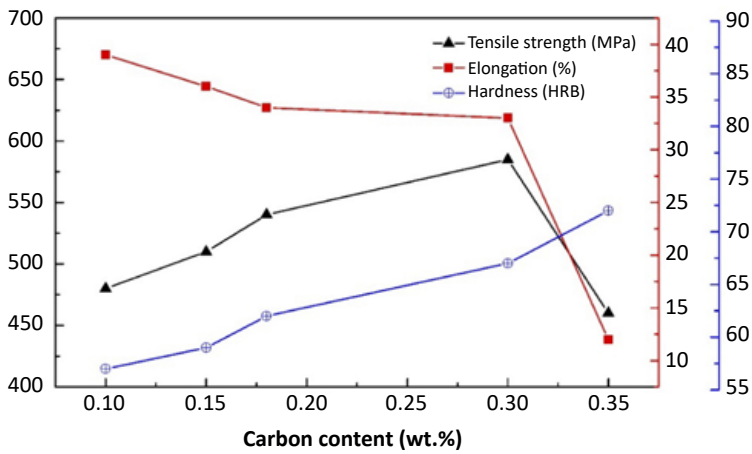

Fig. 9 Mechanical properties of MIM 316L stainless steel with different carbon contents [4]

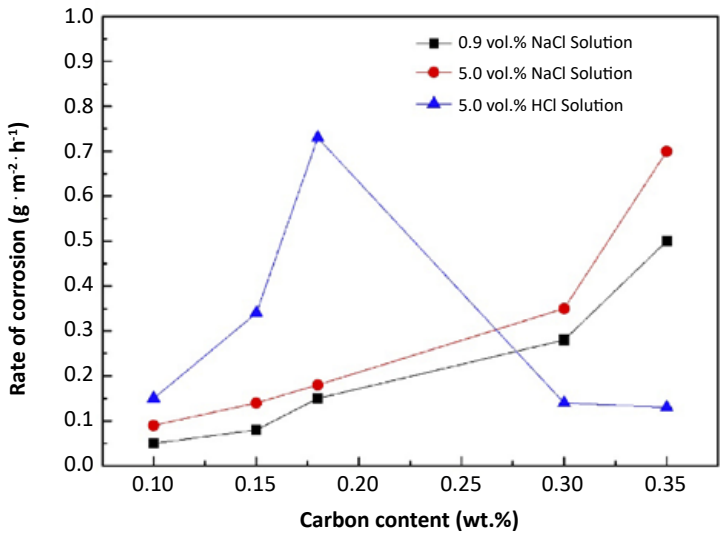

Fig. 10 Corrosion resistance of MIM 316L after immersion in different solutions for 72 h [4]

with the same packing pressure and time mentioned above. The same optimised moulding parameters were used for all three feedstocks to produce green parts without any moulding defects such as sink marks, voids and flow lines. The moulded parts were debound and sintered in a high-temperature vacuum furnace, and the sintered parts from the chosen feedstock formulations were examined for dimensional change during sintering deformation. This was done by measuring the width of the part with dimensional tolerance (24+0.05 / -0.25 mm) and analysing the leg opening in the vertical section of the part. The higher the leg opening, the higher the level of distortion and vice versa.

From the deformation studies, feedstock containing 7-8 µm powder showed a lower distortion compared to the 10 µm gas atomised powder (Fig. 8). This the authors attributed to the inherent characteristics of the powder, especially lower particle size. The extent of leg opening in the sintered component was higher in 10 µm gas atomised powder compared to the 7-8 µm gas/water atomised powder.

Novel stainless steel and NiTi stents produced by MIM

Stents for coronary artery diseases have been deployed for a number years by slipping the stent into the artery after a balloon angioplasty. The stent is then opened to keep the artery open permanently. Stents have been produced from biocompatible stainless steels (316L), NiTi alloy, and cobalt-chromium alloys mainly using laser cutting or metal wire knitting as the manufacturing processes. Some are coated with polymer-plus-drug coating and are known as drug-eluting stents. These coatings can contain micro-reservoirs of a drug to act as a functional drug delivery vehicle.

However, the laser cutting process involves high cost, with low production rates and non-uniform microstructures making the stents

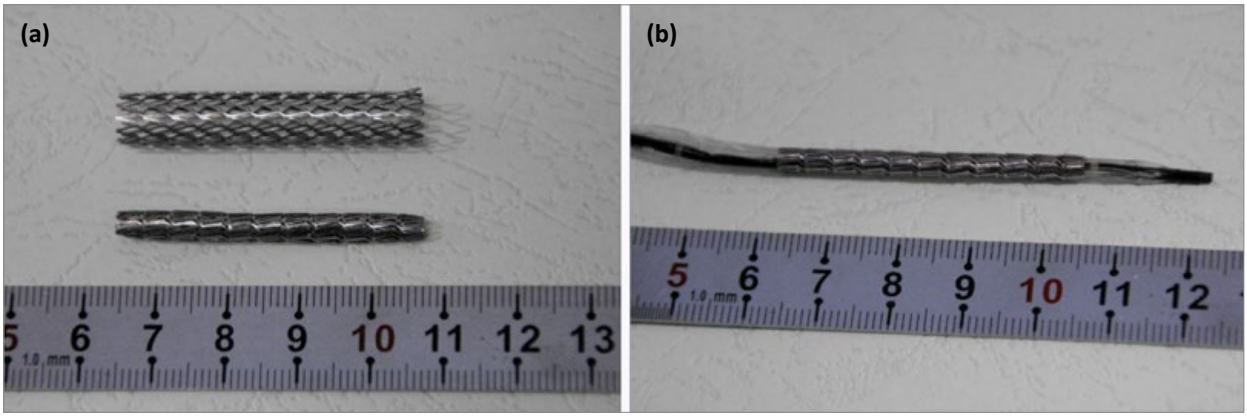

Fig. 11 Novel MIM 316L stent in (a) expanded and compressed state, and (b) compressed state with a balloon [4]

expensive. A collaborative research project undertaken by leading universities, medical research centres and a MIM producer in China, has been investigating the use of Metal Injection Moulding to produce novel small and complex-shaped stents more economically and with improved properties compared with laser cutting or metal wire knitting. He Hao (Guangxi University of Science and Technology, Liuzhou) and colleagues reported on their initial findings on producing MIM 316L stainless steel and also NiTi memory alloy stents in a paper presented at the WORLDPM2018 Congress [4].

The researchers focused on using gas atomised 316L stainless steel powder which was mixed with a multi-component binder system comprising paraffin wax and Low Density Polyethylene (LDPE) to produce the MIM feedstock. Powder loading in the feedstock was 60-65 vol.%. NiTi feedstock for injection moulding was also prepared. The feedstocks were moulded in a BOY 50T2 injection moulding machine to produce tensile test pieces and novel stents followed by solvent and thermal debinding, and sintering at different temperatures in low and high vacuum respectively.

Fig. 9 shows the tensile strength, elongation and hardness properties of the 316L MIM samples as a function of carbon content. As can be seen, a rise in carbon content above 0.3% results in a drastic drop in strength and elongation. This is attributed to a number of large pores and grain growth found in the sintered 316L MIM parts at this carbon level. However, the authors stated that the mechanical properties of the MIM 316L stents can be tailored to the specific clinical requirements by adjusting the carbon content, and also by appropriate stent design. A further advantage to MIM is that stents can be produced with a controlled pore structure using the space holder technique. The resulting porosity in the MIM stents can be used as a drug carrier to replace the conventional drug-eluting stents having a polymer coating, and thereby reducing the long term risks of thrombus, the formation of harmful clots, and restenosis, the abnormal narrowing of an artery or valve after corrective surgery.

The authors also studied the corrosion rate of the MIM 316L stainless steel stents after immersion in different solutions, and found that corrosion resistance decreases with increasing carbon content especially in NaCl solution (Fig. 10). Corrosion resistance was found to be acceptable when carbon content is below 0.2 wt.%. In HCl solution the corrosion rate is much higher than in NaCl when the carbon content is not higher than 0.2 wt.%, and further work is being done to understand the mechanism for this.

"the MIM 316L stents can be tailored to the specific clinical requirements by adjusting the carbon content, and also by appropriate stent design. A further advantage to MIM is that stents can be produced with a controlled pore structure..."

An example of the novel MIM 316L stainless steel stent produced in the research project is shown in Fig. 11. The novel MIM stent was successfully implanted into the aorta of several groups of adult dogs and has shown excellent biocompatibility and safety. Further work is being done to investigate the mechanical properties of the novel MIM 316L stents and also on animal testing.

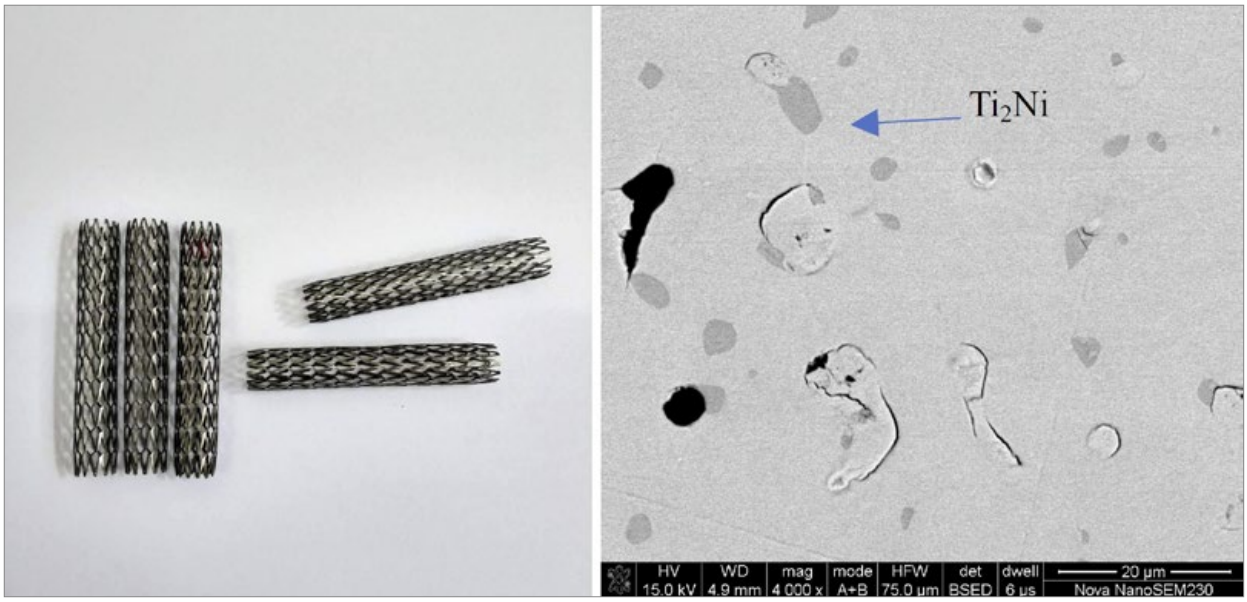

Fig. 12 MIM NiTi stents sintered at 1250°C have a density greater than 95% [4]

The researchers also briefly reported on the use of NiTi shape memory alloy to produce novel MIM stents for implanting. They stated that a density above 95% can be obtained at 1250°C sintering temperature and with low interstitial (oxygen and carbon) content in the NiTi alloy in order to maintain the shape memory effect. MIM NiTi stents produced are shown in Fig. 12, and additional research is also being done on properties and animal testing.

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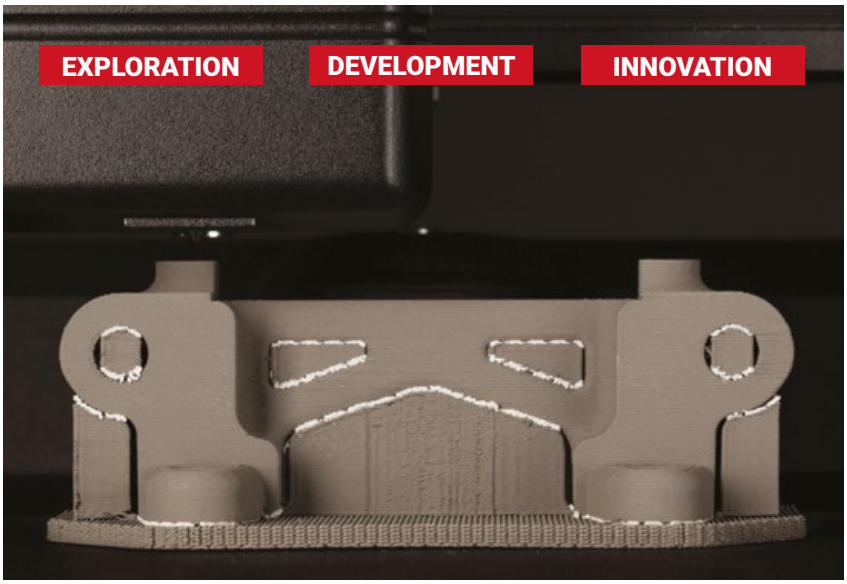

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Euro PM2018: Research into the characterisation of MIM products and feedstocks

A number of papers presented at the Euro PM2018 conference, organised by the European Powder Metallurgy Association (EPMA) and held in Bilbao, Spain, October 14-18, 2018, addressed issues relating to the evaluation of MIM product properties and relevant feedstock characteristics. Dr David Whittaker reviews three papers on the mechanical characterisation of biocompatible Co-Cr-Mo alloys, the corrosion resistance of MIM 17-4 PH and the characterisation of MIM-like feedstocks for Fused Filament Fabrication.

Mechanical characterisation of MIM-processed biocompatible Co-Cr-Mo alloys

A paper by Juan Alfonso Naranjo, Cristina Berges, Ignacio Garrido and Gemma Herranz (Universidad de Castillo-La Mancha, Spain), addressed the dynamic and static mechanical properties of MIM-processed biocompatible Co-Cr-Mo alloys [1]. Metallic alloys based on Co-Cr-Mo are known to exhibit excellent corrosion resistance and biocompatibility, as well as high wear resistance and good mechanical properties. However, few studies have been published which relate to the fatigue strength of these biomaterials when produced by Metal Injection Moulding.

In the reported study, samples made from Co-Cr-Mo alloy containing low carbon (≤ 0.1 wt.%) were successfully manufactured by MIM, and their wear resistance and hardness studied, as well as their static mechanical properties in terms of tensile and bending strength. The dynamic mechanical behaviour and durability of this biomaterial (fatigue properties) were also examined.

A Co-Cr-Mo pre-alloyed material (ASTM F75), containing 0.085 wt.% C and less than 0.1 wt.% Ni, was used in the study. The metallic powder showed a rounded shape with particle size distribution (D90) lower than 18 µm and an absolute density of 8.20 g/cm^3. Feedstock used in the MIM process was produced by mixing the appropriate amount of Co-29Cr-6Mo powder (65 vol.%) (composition as given in Table 1) with a thermoplastic binder containing high-density polyethylene and paraffin wax. Green parts free of defects, in rectangular and 'dog bone' geometries, were obtained

Fig. 1 Euro PM2018 took place at the Bilbao Exhibition Centre, BEC (Photo © Andrew McLeish / Euro PM2018)

	C	Ni	Si	Mn	Cr	Fe	Mo	Co
Co-Cr-Mo powder	0.085	0.01	0.79	0.41	28.57	0.04	5.87	Balance
ASTM F75	< 0.35	< 0.50	< 1	< 1	27-30	< 0.75	5 < 7	Balance

Table 1 Chemical composition of the Co-Cr-Mo powder (wt.%) [1]

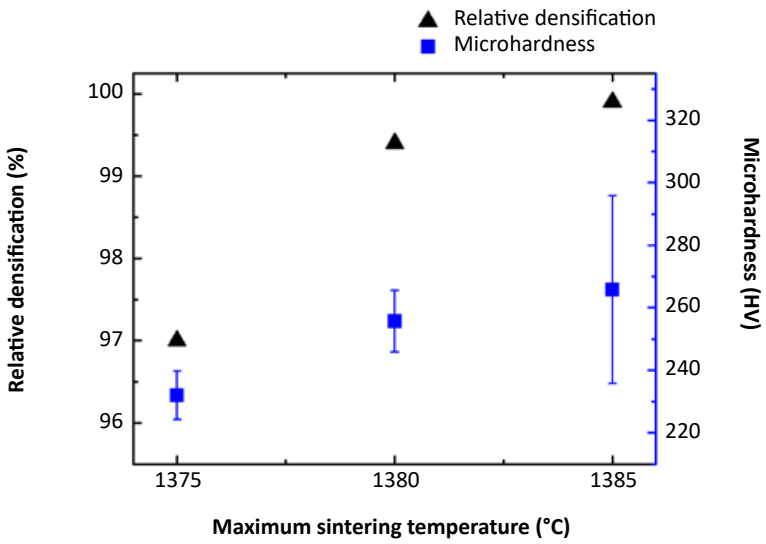

Fig. 2 Relative densification and microhardness at different maximum sintering temperatures [1]

after injection moulding in an Arburg 270s machine. Debinding was carried out in two steps; solvent debinding by immersion in heptane followed by thermal debinding in an adapted furnace. Sintering was carried out in a vacuum atmosphere in a tubular furnace in the range 1375–1385°C for 1 h, resulting in a high level of densification.

In the rectangular specimens, relative densification, microhardness and microstructural characterisation were assessed at three different sintering temperatures, where relative density is above 97%. This characterisation allowed the determination of the optimum sintering temperature. Fig. 2 shows the obtained densification and microhardness. Densification and microhardness both increase with the maximum sintering temperature.

Microstructural characterisation was conducted on samples sintered at the three temperatures considered. At 1375°C, the lower density shown in Fig. 2 is confirmed with a greater number of pores. These were rounded and small, indicating that the process was close to the optimum sintering temperature. At 1385°C, a large number of intergranular carbides and Si-rich inclusions within precipitated carbides were detected. The 'blocky' intergranular carbides were identified as being of the $M_{23}C_6$ composition. Massive grain boundary carbides could produce a reduction of ductility and fatigue strength; on the other hand, completely clean grain boundaries without carbides could result in a reduction of strength, so an adequate compromise between these two extremes is achieved with a sintering temperature of 1380°C. The optimum conditions, employed from green specimens to the final samples, and the obtained properties, are presented in Table 2.

Mechanical characterisation, in terms of bending resistance and tensile strength, employed rectangular and dog bone test pieces, respectively.

Bending resistance studies were carried out on parts sintered at three sintering temperatures (1375°C, 1380°C and 1385°C). Flexural modulus of elasticity (E_f), yield strength (σ_y) at 0.2% permanent deformation, flexural strength (σ_f), elongation at fracture and energy

Maximum debinding temperature	430°C
Maximum sintering temperature	1380°C
Relative density achieved	99.6%
Final carbon content	0.10%
Microhardness	260 HV

Table 2 Conditions and final characteristics of specimens [1]

Sintering T (°C)	E_f (MPa)	σ_y 0.2% (MPa)	σ_f (MPa)	Elongation (%)	Energy until break (J)
1375	59563	551	1705	23	34
1380	49878	657	1433	18.5	22
1385	32519	530	1346	12	15

Table 3 Bending test values for different sintering maximum temperatures [1]

at fracture were calculated. These values are given in Table 3. The tension curves obtained in the test are shown in Fig. 3. These results reflect a decrease in calculated mechanical parameters at 1385°C, which may be due to the massive presence of carbides in the grain boundaries when sintering temperature increases.

In the case of the tensile tests, stress-strain behaviour was evaluated and Young's modulus (E), yield strength (σ_y) at 0.2% permanent deformation, ultimate tensile strength (σ_{max}) and maximum elongation values calculated. These are presented in Table 4. These results correspond to the samples sintered at the optimum sintering temperature. The final carbon contents and the values obtained by other authors are also included. Comparing the results in this study with those reported at 0.23 wt.%C, similar yield and tensile strength were achieved, while the higher ductility achieved in this study (15% elongation) can be attributed to a reduced presence of carbides.

With regard to the dynamic mechanical behaviour of this material, four-point bending fatigue tests have also been investigated. In Fig. 4 (left), the number of cycles each specimen resisted as a function of the maximum bending stress imposed is presented. The cycles to failure decrease with the increase of maximum bending stress. Extrapolated values to 10^6 and 10^7 cycles to failure indicate 393 and 254 MPa of maximum bending stress, respectively. It can therefore be assured that this material is valid for biomedical applications, as it is above 200 MPa at 10^7 cycles.

In Co-Cr-Mo alloys, the austenitic phase (FCC structure) can coexist with the martensitic phase (HCP

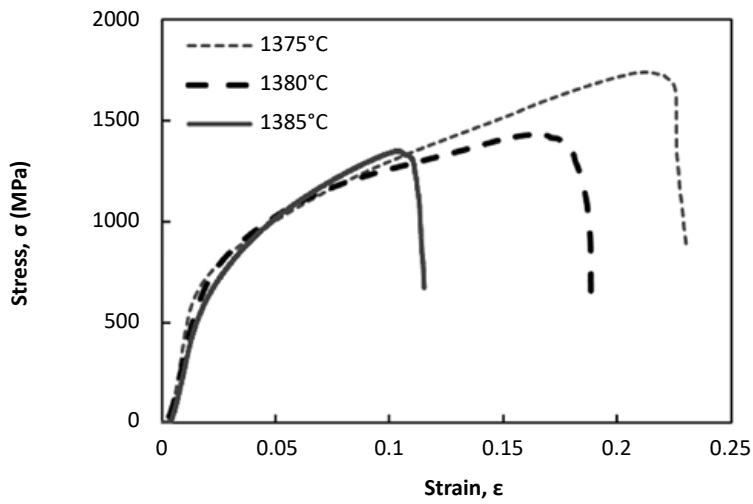

Fig. 3 Bending test for different sintering maximum temperature [1]

	C (wt.%)	E (MPa)	σ_y 0.2% (MPa)	σ_{max} (MPa)	Elongation (%)
This work	0.10	164273	420	683	15
Vieira, 2009 [5]	0.23	-	426	695	10
	0.35	-	604	889	6

Table 4 Stress-strain behaviour of Co-Cr-Mo specimens [1]

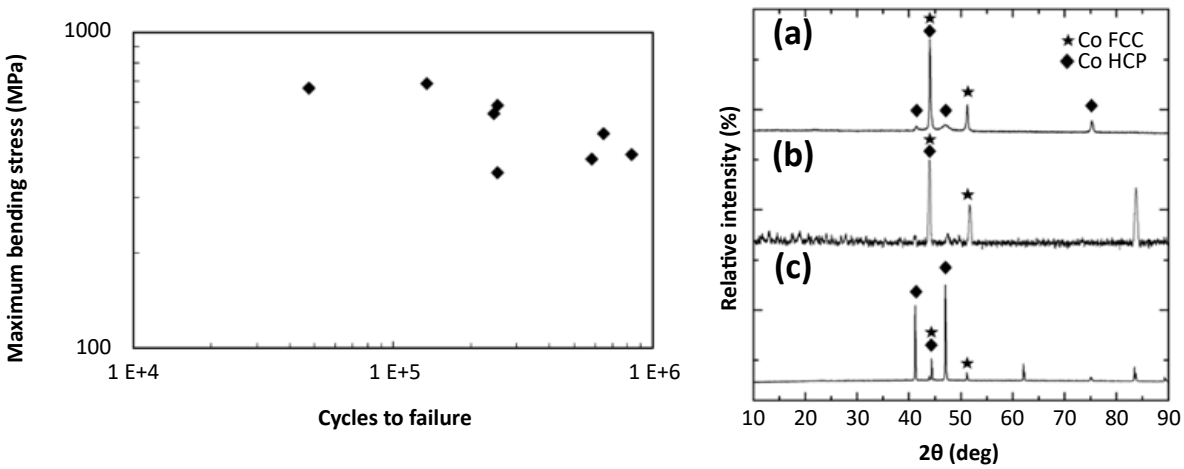

Fig. 4 Values for the bending fatigue test (left) and X-ray diffraction diagram (right) of: (a) Co-Cr-Mo powder, (b) as sintered specimen and (c) after fatigue test [1]

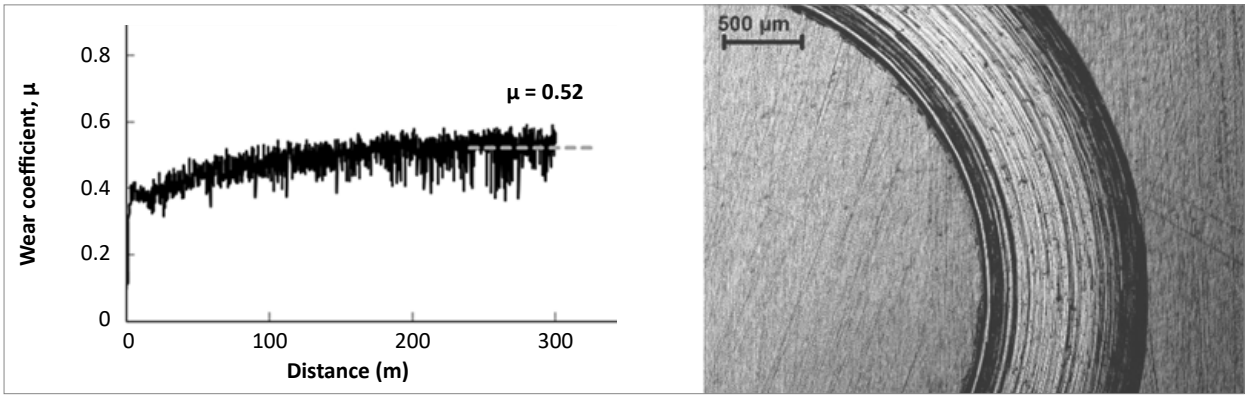

Fig. 5 Wear coefficient with distance (left) and groove obtained after the pin-on-disk test (right) [1]

structure), but the latter provides higher hardness and wear resistance and improves fatigue behaviour. The transformation of the FCC microstructure to HCP can be achieved by thermal treatment or by deformation. In the reported work, the phase transformation induced by deformation in the fatigue test has been analysed. For this purpose, X-ray diffraction studies were performed and these confirmed that the microstructural change took place. Figs. 4(a) and (b) (right) show the results of X-ray diffraction studies applied to the Co-Cr-Mo metal powder and a sintered part before fatigue testing. The results indicate a predominance of the FCC structure in the powder and in the sintered part. After fatigue testing (Fig. 4(c) (right)), a significant increase of HCP structure is detected, proving the role of the deformation-induced martensitic transformation.

The tribological behaviour of the material sintered at the optimum temperature has also been studied. Fig. 5 indicates the wear coefficient registered by the tribometer. The stabilised value indicates the wear coefficient characteristic of the material, which is 0.52. Calculated values of wear rate result in $3.03 \cdot 10^{-4}$ $mm^3/N \cdot m$. This value is similar to those found in the literature for alloys of low carbon content processed by other methods, confirming MIM as an adequate technology for Co-Cr-Mo processing. Furthermore, the tribological behaviour of parts after fatigue bend testing has been investigated. A remarkable increase is observed in the wear resistance, leading to values above 0.76 for the wear coefficient and $1.19 \cdot 10^{-5}$ $mm^3/N \cdot m$ for the wear rate. These values can be explained because of the increase of the proportion of the HCP structure.

The influence of the martensitic phase on mechanical properties will be covered in a future study. According to the presented analysis, MIM technology is proven as an appropriate processing method for this type of cobalt alloy.

Material	Process
17-4 PH Master Alloy 1	Sintering + Aged + Soft Tumbling
	Sintering + Aged + High Tumbling
	Sintering + Soft Tumbling
	Sintering + High Tumbling
17-4 PH Master Alloy 2	Sintering + Aged + Soft Tumbling
	Sintering + Aged + High Tumbling
	Sintering + Soft Tumbling
	Sintering + High Tumbling
17-4 PH Atomised	Sintering + Aged + Soft Tumbling
	Sintering + Aged + High Tumbling
	Sintering + Soft Tumbling
	Sintering + High Tumbling

Table 5 Different types of 17-4 PH, heat treatment and surface treatment of dog bones [2]

Investigation into the corrosion resistance of MIM 17-4 PH

A paper from Juan Francisco Pérez and Manuel Caballero (Mimecrisa, Spain) focused on the corrosion resistance of MIM 17-4 PH stainless steel [2]. An analysis of corrosion data in the public domain for 17-4 PH stainless steel processed by Metal Injection Moulding, drawn from the ASTM B883 and ISO 22068 standards and arising from work in the European Thematic Network on Standards for Metal Injection Moulding, concluded that these data were inconclusive, particularly regarding

the influence of MIM processing conditions. The reported project was therefore set up to address this issue.

The selected corrosion test method was the Neutral Salt Spay (NSS) test, according to ISO 9227. Standard dog bones for tensile testing were manufactured with different types of feedstock, two using master alloy powder from two different suppliers and one using atomised powder. Also, samples were manufactured with different thermal treatments and surface treatments, to study the influence of surface finish on corrosion resistance. The different thermal treatments used were sintering (in all cases), with half of the test samples being aged subsequently. Afterwards, all samples were surface treated by soft tumbling, with some also being subjected to high tumbling (lower final roughness). All versions of dog bones tested are shown in Table 5.

All of the dog bones were sintered in the same continuous furnace, with the same sintering cycle (temperature and time) and under the same atmosphere (H_2/Ar). The same heat treatment was also repeated in all the cases in which it was applied (aged H900 condition). The corrosion test was carried out for 96 hours, with examination after 24 hours (Fig. 6). During this examination, the corrosion was noted (corrosion type, extent, location) and a final synthesis carried out at the end of the test.

The type of corrosion sought in the inspection was the appearance of red oxide. Table 6 shows the results obtained after 24 hours of testing and final inspection at 96 hours of testing. As can be seen, red oxide appeared in almost all variants, with the exception of the dog bones that had been sintered, aged and high tumbled and which, in all cases, underwent 96 hours of testing without the appearance of red oxide. The appearance of red oxide occurred, in all cases, around the injection gate of the parts, as this is an area with segregation (separation of the powder and binder).

Densities and %C were measured in the dog bones marked in green in Table 6, the results being presented in Table 7.

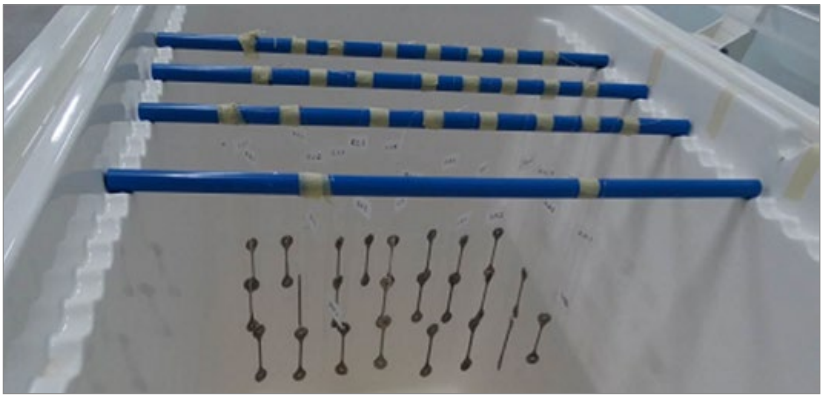

Fig. 6 Inspection of dog bones after 24 hours of testing [2]

Taking into account these results, a further test with sintered, aged and strongly-tumbled parts was carried out, prolonging the trial up to 300 hours. In this case, and because the red oxide generally appeared in the gate of the parts, the gate in the green parts was polished before sintering. The results obtained were satisfactory for all of the tested 17-4 PH, without red oxide on any part in all of the inspections (Table 8).

Based on the results in the reported study, the authors have concluded that surface finish of the test pieces is a very significant determinant of corrosion resistance. Once the density is sufficiently high and the carbon level as low as possible, good results are connected

Material	Process	0 h	24 h	96 h
17-4 PH Master Alloy 1	Sintering + Aged + Soft Tumbling		RO	
	Sintering + Aged + High Tumbling			
	Sintering + Soft Tumbling		RO	
	Sintering + High Tumbling		RO	
17-4 PH Master Alloy 2	Sintering + Aged + Soft Tumbling		RO	
	Sintering + Aged + High Tumbling			
	Sintering + Soft Tumbling		RO	
	Sintering + High Tumbling		RO	
17-4 PH Atomised	Sintering + Aged + Soft Tumbling		RO	
	Sintering + Aged + High Tumbling			
	Sintering + Soft Tumbling		RO	
	Sintering + High Tumbling			RO

Table 6 Results of red oxide appearance at 24 and 96 hours after the NSS test [2]

Material	Density	%C
17-4 PH master alloy 1	7.65 g/cc	0.004
17-4 PH master alloy 2	7.61 g/cc	0.005
17-4 PH atomised	7.67 g/cc	0.018

Table 7 Density and %C of sintered + aged + high tumbling dog bones [2]

Material	Process	72 h	96 h	120 h	144 h	168 h	240 h	300 h
17-4 PH Master Alloy 1	Sintering + Aged + High Tumbling							
17-4 PH Master Alloy 2	Sintering + Aged + High Tumbling							
17-4 PH Atomized	Sintering + Aged + High Tumbling							

Table 8 Salt spray tests on sintered, aged and high tumbled samples up to 300 h of exposure

to heat treatment, microstructure and surface finishing. As an aspect of potential future work, there is an interest in evaluating dog bone samples coated with nanomaterials.

Characterisation of stainless steel feedstocks for Fused Filament Fabrication

The final paper reviewed also came from the group at Universidad de Castilla-La Mancha, the authors being Cristina Berges, Juan Alfonso Naranjo and Gemma Herranz. This paper addressed the characterisation of printable stainless steel feedstocks for a 'MIM-like' Additive Manufacturing process, Fused Filament Fabrication (FFF) [3].

Fused Filament Fabrication, using metal or ceramic-based filaments, can be a cheap, fast and straightforward means for the tool-free production of components with highly complex designs. The concept has been considered as a rapid PIM-prototyping process, able to complement the current state-of-the-art in applications such as injection moulding die or insert production. It offers the possibility of component customisation and validation before entering the high-volume production stage. A proper FFF process requires the achievement of optimum properties in the original filaments, in terms of viscosity, adhesion behaviour, flexibility to be spooled and stiffness. On the other hand, detailed study of debinding optimisation also needs to be carried out. The main objective of the reported study has been to investigate the feasibility of printing metal-based filaments, containing different polymers, using conventional FFF machines. Therefore, rheological behaviour, mechanical and thermal characterisations have been investigated in order to further understand the whole process and select the optimum materials for this application. The resultant green prototypes were subsequently debound and sintered in a comparable way to the PIM parts.

Different thermoplastic polymer mixtures (binder system) have been filled with stainless steel powder at a concentration of 50 vol.% using a double rotor mixer. The mixing conditions were set at 30 rpm and different temperatures for a duration of 120 min to obtain homogeneous mixtures. Certain levels of additives to ensure compatibility between powder and binder have also been used. The studied range of polymers provided either stiffness or flexibility to the subsequent filament, by combining mixtures of one or two of these polymers so that the filament's final properties were tuned. For reasons of confidentiality, the authors did not divulge details of the main polymers incorporated in the binder system of filaments a-e.

Prepared filaments were visually examined in order to evaluate their flexibility under bending deformation. As can be seen in Fig. 7,

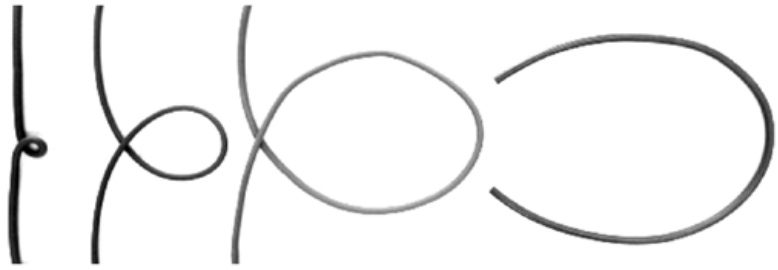

Fig. 7 Filament flexibility from left to right: a/b, c, d and e [3]

Filament	Mixing T (°C)	Filament producing T (°C)	Printing T (°C)
a	250	180	-
b	175	140	-
c	240	180	300
d	185	140	220
e	200	150	200

Table 9 Processing temperature selected for mixing, filament production or printing of each material [3]

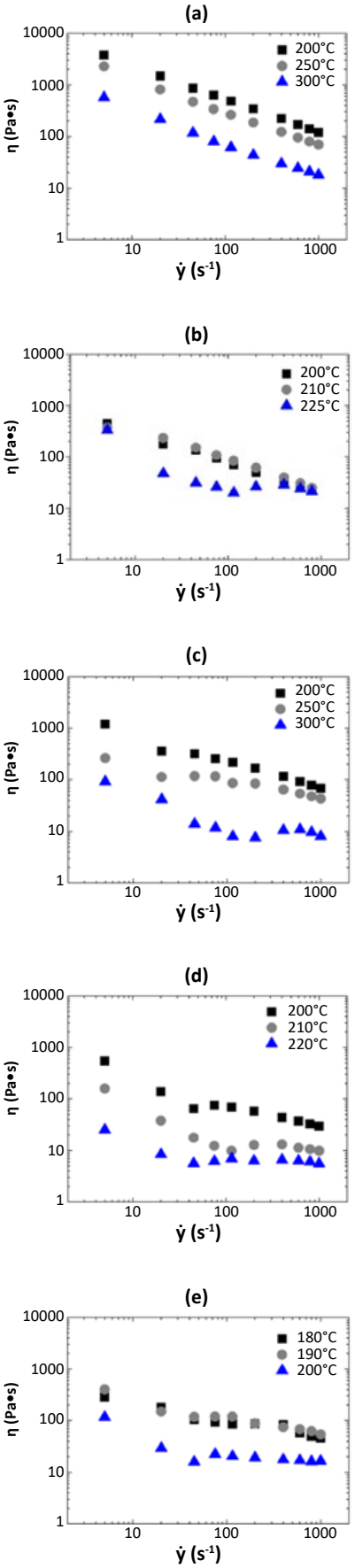

Fig. 8 Viscosity (η) vs shear rate (γ) measurements of filaments a-e [3]

filaments decreased in flexibility from a to e, while stiffness increased.

Printing by FFF was investigated over a wide range of temperatures with the fabricated filaments a-e and the optimised processing temperatures are shown in Table 9. Printing trials in the case of filaments a and b failed, even at high temperature (300°C), since the melted material became adhered at the nozzle output. These filaments were too flexible and soft to exert enough force in the hot zone of the printer, and additionally they could not pass through the nozzle smoothly to be deposited on the bed. Further adjustments to the printer system will be required to consider these materials as feasible feedstock for FFF. On the contrary, filaments c, d and e were successfully printed, at 300°C in the case of c and at around 200°C for d and e, as can be seen in Table 9. Flexibility and stiffness were adequate for these filaments. However, filaments d and e broke when feeding the extruder head, as they were too brittle to endure the feeder force. Shorter filaments were manually fed into the extruder head for use and different machine designs can be further studied to achieve continuous feeding from the spool for these material types. Thus, the best results were obtained with filament c, being the optimum from the studied range.

In order to explain the rheological behaviour of the filaments during printing, viscosity measurements were conducted with the prepared mixtures at different temperatures (according to their processing temperatures; see Table 9). Once the mixtures were available in pellet form, their rheological properties were studied in a capillary rheometer. Experiments were carried out varying the temperature between 180°C and 300°C, depending on the material, at selected shear rates between 5 and 1000 s^{-1}. A die having L/D=10 and a 0-1400 bar pressure sensor were used. From these designed mixtures, filaments a-e were produced in a single-screw extruder at temperatures in the range of 100–150°C, equipped with

Filament	Experiment T	n	E_a (kJ/mol)
a	200°C	0.356	46
	250°C	0.353	
	300°C	0.355	
b	200°C	0.443	100
	210°C	0.439	
	225°C	0.598	
c	200°C	0.503	73
	250°C	0.695	
	300°C	0.600	
d	200°C	0.530	190
	210°C	0.567	
	225°C	0.833	
e	200°C	0.721	140
	190°C	0.513	
	180°C	0.683	

Table 10 Rheological parameters: flow index (n) and activation energy (E_a) calculated from viscosity measurements at different temperatures for each material. For E_a calculation, values at 100 s^{-1} shear rate were taken into account [3]

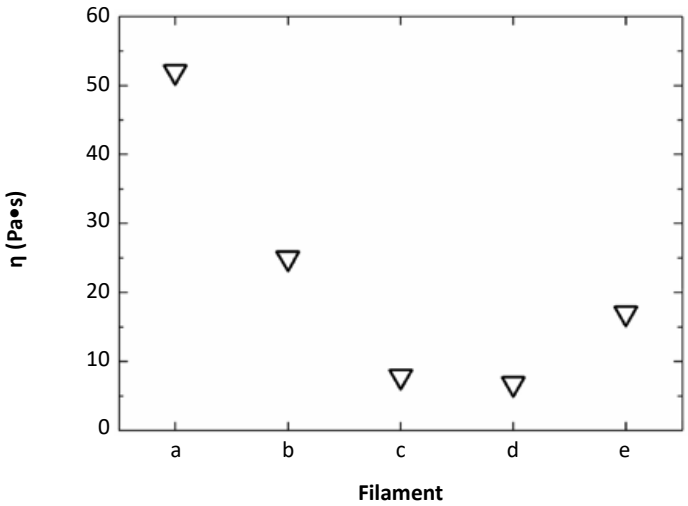

Fig. 9 Viscosity values (average values calculated in the selected range of 100 –200 s^{-1}) of filaments a-e determined at the highest studied temperature for each filament [3]

the accessory to wind the filament in a spool, allowing large batches to be produced. Filament diameters were set at 1.75 ± 0.05 and 2.85 ± 0.05 mm.

Fig. 8 shows the viscosity evolution with the selected shear rates. In all cases, viscosity values decreased with increasing shear rate, indicating a pseudoplastic behaviour, and with increasing temperature. Despite being one of the most flexible filaments, filament a presented the highest viscosity values, even at 300°C.

Viscosity dependences on shear rate and temperature have been studied by determining the flow index (η) and the activation energy (Ea) respectively, according to the following equations:

$$\eta = k\dot{\gamma}^{n-1}$$

$$\eta = \eta_0 exp(\frac{Ea}{RT})$$

The results obtained with the different mixtures are displayed in Table 10. In all cases, a flow index parameter η<1 was determined. The lowest η values were recorded for filament a, corresponding to the highest pseudoplastic characteristic. Higher η values obtained with the rest of the filaments, especially at the most elevated temperatures, indicated lower pseudoplasticity. In fact, in the cases measured at the highest temperature, two different behaviours were observed (pseudoplastic at shear rates lower than 100 s^{-1} and Newtonian at higher shear rates). n values were calculated taking into account all points in the curve. On the other hand, filaments a and c showed the lowest values of activation energy, meaning that these materials present the lowest dependence of viscosity on temperature, a desirable effect during the printing stage to ensure process robustness.

According to the results obtained in the rheological study, higher flexibility is not necessarily related to lower viscosity behaviour under shear forces, even at high temperatures (300°C), as was confirmed with filament a. Viscosity measurements can predict the printability and the optimum printing temperature of filaments, considering the typical shear rates in the range of 100 to 200 s^{-1}. It can be concluded that viscosity values lower than approximately 20 Pa·s are required for an adequate filament printing process in the selected shear rate range. This situation corresponds with the properties of filaments c, d and e. Otherwise, clogging in the nozzle takes place, resulting in non-printable materials, as was observed in filaments a and b. Fig. 9 shows the viscosity (average values in the range of 100 to 200 s^{-1}) of filaments a-e at the highest studied temperature. In the case of filament c, a temperature increase of up to 300°C was needed to reduce viscosity, while lower temperature was sufficient for filaments d and e. Moreover, the low viscosity requisite is more important than a larger degree of pseudoplasticity (filament a), as was verified by the flow index (η) previously calculated.

The mechanical characterisation of the filaments was investigated. In particular, tensile tests were conducted and Young's modulus (E), ultimate tensile strength (σ_{max}) and maximum elongation (ε_{max}) values were calculated. A tensile testing machine with a 50 kN load cell was used and tensile tests were performed at room temperature, fixing the filaments to a support, setting the initial length to 40 mm and ensuring that they fractured adequately. At least five specimens of each type of filament were pulled

Filament	Young modulus E (MPa)	σ_{max} (MPa)	ε_{max} (%)
a	20.8 ± 0.2	3.0 ± 0.2	60 ± 9
b	18.2 ± 0.3	0.6 ± 0.1	20 ± 2
c	140.6 ± 0.2	4.2 ± 0.3	6.0 ± 0.5
d	82.7 ± 0.3	2.8 ± 0.4	3.0 ± 0.2
e	149.8 ± 0.3	4.6 ± 0.4	3.5 ± 0.2

Table 11 Young's Modulus E, ultimate tensile strength and maximum elongation values of filaments a-e [3]

at 10 mm/min speed until fracture and the average measurement was used for parameter calculation. The calculated results are displayed in Table 11.

Filament a had a very high elongation at fracture (around 60%) and a long plastic region up to failure. Filament b showed a certain elongation at fracture (20%) but a necking effect was observed leading to stress decay before failure. In both cases, the stress presented a very small elastic region. Filaments c, d and e showed lower elongation at fracture (< 10%) and high ultimate tensile strength values (e > c > d). In particular, the highest Young's modulus was obtained in the case of filament c and lower elongation values for filaments d and e (d & e < c), which resulted in brittler and stiffer behaviour than filament c. These differences can explain the modifications needed in these three filaments to feed the FFF Additive Manufacturing system. The brittleness shown by filaments d and e meant that they could not be spooled, as they were broken when passing through the feeder.

From the printing feasibility point of view, filaments a and b showed poor mechanical behaviour with too high a plasticity under tensile forces, i.e., too low a stiffness for the melted material to be extruded through the nozzle. Therefore, they were discarded as non-printable materials in the system; while filaments c, d and e showed acceptable mechanical properties, especially c, with a certain degree of flexibility and stiffness, allowing a continuous filament feeding from the spool to the extruder. Therefore, green parts were accomplished by printing filaments c, d and e and good adhesion between layers upon melt deposition was proved.

After filament printing in a conventional FFF machine (with a 0.4 mm nozzle), thermal characterisation of those filaments successfully printed was carried out by thermogravimetric analysis. Heating rates of 5°C/min up to 600°C were employed.

Debinding cycles were designed according to the thermogravimetric studies. Thermal debinding of the resultant green parts was performed under different atmospheres (N_2, N_2-H_2 5wt and N_2-H_2 10 wt.%).

Weight loss varied from 10 to 14 wt.%, depending on the particular binder system. In all cases, two different weight loss regions were observed, being more accentuated in the case of filament d. This effect is desirable for the achievement of effective and gradual polymer decomposition during the thermal cycle, such as the typical MIM debinding process. Different conditions during solvent and thermal debinding steps were tested and an optimised cycle was set in the case of filament c, which allowed the attainment of brown parts without distortion or defects. However, binder swelling was observed after debinding of filaments d and e, even at very low debinding rates. Trials under more reducing

atmospheres (N_2 with 5 and 10 wt.% of H_2) were performed, which can accelerate the thermal decomposition at lower temperatures. The swelling effect was partially minimised on increasing hydrogen concentration. Pure hydrogen atmosphere is expected to reduce defects, but safety limitations regarding the use of hydrogen-based atmospheres at laboratory scale led the authors to discard filaments d and e.

Finally, sintering of high-quality brown parts from filament c was carried out and optimised at temperatures in the range of 1380–1390°C in a tubular furnace under vacuum at a heating rate of 5°C/min up to the maximum sintering temperature, which was maintained for 1 hour, and the sintered parts were cooled slowly inside the furnace, with highly densified final parts being successfully obtained (≥ 95%). Therefore, filament c was selected as the most appropriate material that allows the accomplishment of the metal manufacturing process by FFF.

Further mechanical studies, such as compression buckling tests, which would also provide data on filament characteristics during extruder feeding, are currently under investigation; as well as special extruder components and feeder mechanisms for highly flexible or brittle filaments.

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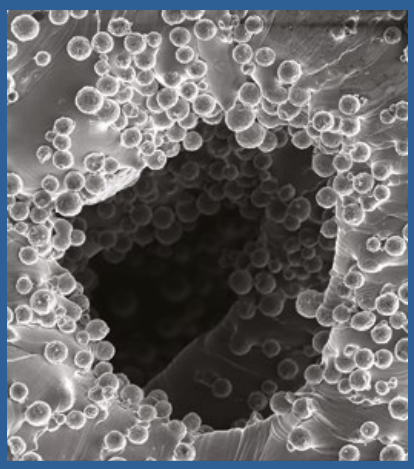

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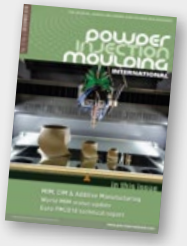

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