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FOR THE METAL, CERAMIC AND CARBIDE INJECTION MOULDING INDUSTRIES

POWDER INJECTION MOULDING INTERNATIONAL

in this issue

Profiles: USD & UCLM PIM Laboratory

MIM superalloys research

Energy efficiency in MIM

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POWDER INJECTION MOULDING INTERNATIONAL

For the metal, ceramic and carbide injection moulding industries

MIM continues to progress in the aerospace sector

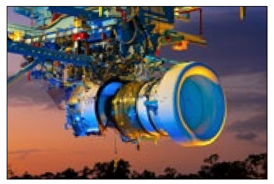
The aerospace industry is today one of the most important global growth markets for MIM technology, with superalloys and titanium being key materials. Whilst aerospace manufacturers compete in a race to announce their latest milestones in the use of metal Additive Manufacturing, they are generally far more discrete about publicising the advances that are currently taking place in MIM for aerospace applications.

When announcements do happen, they can give the impression of rapid advances for both MIM and AM in the aerospace sector. These developments have, of course, to be seen in the context of a long period of development, testing and qualification spanning several decades, with MIM superalloy research dating back to the 1980s.

What is clear is that developers of MIM aerospace components are fiercely protective of their processes and technologies and this has lead to significant volumes of MIM related patents being issued worldwide. Whilst it is well known that an industry such as aerospace is an IP rich environment, there is concern amongst many in the wider MIM industry that some of these patents may not recognise, for example, industry processes that are common-place amongst part producers.

As our review of just a small selection of recent research papers shows, activity in this area of MIM is truly global, with aerospace corporations and research institutions pushing the technology forward in North America, Asia and Europe.

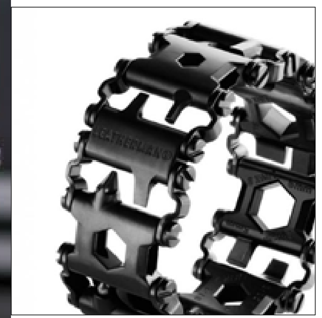
Nick Williams
Managing Editor



Cover image
A PW1524G engine during ground testing in West Palm Beach, USA. The engine uses both MIM and AM components
(Photo © Pratt & Whitney)

June 2015

POWDER INJECTION MOULDING INTERNATIONAL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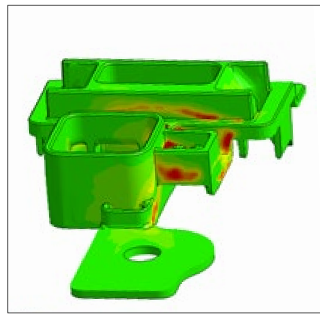
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Regular features

Industry News

To submit news for inclusion in *Powder Injection Moulding International* please contact Nick Williams, nick@inovar-communications.com

Pratt & Whitney's new PurePower® jet engines feature MIM and AM parts

Pratt & Whitney has announced that when it delivers its first production PurePower® PW1500G engines to Bombardier this year, the engines will include Metal Injection Moulded components as well as being the first to feature entry-into-service jet engine parts produced using Additive Manufacturing.

The PurePower engine family parts will be the first product produced using 3D printing powder bed Additive Manufacturing. Related manufacturing technologies to be used in the PurePower engine include Electron Beam Melt and Laser Powder Bed Fusion (including Direct Metal Laser Sintering).

While Pratt & Whitney has produced more than 100,000 prototype parts using Additive Manufacturing over the past 25 years, the company states that it will be the first to use AM technology to produce compressor stators and synch ring brackets for the production engines.

"Pratt & Whitney has been working with Additive Manufacturing since the 1980s and we are looking forward to our upcoming milestone when the first production PurePower PW1500G engines with parts produced through Additive Manufacturing will be delivered," stated Tom Prete, Pratt & Whitney's Engineering Vice President.

"We are a vertically integrated Additive Manufacturing producer with our own metal powder source and the printers necessary to create parts using this innovative technology. As a technology leader, we are intrigued by the potential of Additive Manufacturing to support our suite of technologies and benefits to customers and the global aerospace industry," added Prete.

A PW1524G during testing in West Palm Beach (Photo © Pratt & Whitney)

In production tests, Pratt & Whitney states that it has realised up to 15 months lead-time savings compared to conventional manufacturing processes and up to 50% weight reduction in a single part.

www.pratt-whitney.com

Indo-US MIM Tec reported to be expanding capacity for medical device production

Indian media sources have reported that Indo-US MIM Tec, a leading global supplier of precision-engineered products by Metal Injection Moulding, plans to invest Rs 100 crore in India. The company will make this investment for manufacturing indigenous medical devices. The reports also state that an additional investment of Rs 1,000 crore is also planned globally over the next five years. This is expected to double the company's turnover and manpower.

Indo-MIM designs, manufactures and supplies MIM products for the automotive, medical, consumer, aerospace, oil and gas and industrial sectors to customers in more than thirty countries around the world. The company employs about 3,000 people, of which 500 are reported to be graduate engineers. According to Krishna Chivukula, Chairman and Founder of Indo-US MIM Tec, "The future of Indian job industry lies with India's manufacturing companies and new generation entrepreneurs."

MPIF 2014 award winning MIM parts manufactured by Indo-US MIM Tec Pvt. Ltd. and used in a hearing aid (Courtesy MPIF)

"The new mantra of 'Make in India' will bear fruits only if we are serious about innovation and indigenisation. During 2015 fiscal year and ensuing five years, Indo-MIM plans to aggressively build its capacity," Chivukula is reported to have stated.

www.indo-mim.com

Positive trend continues for MIM in North America

North American Metal Injection Moulding companies reported a positive outlook with sales forecast to continue growing in the years ahead despite a slowdown in growth in 2014.

Peter K Johnson, writing in the *International Journal of Powder Metallurgy* (Vol. 51, No. 1, Winter 2015), stated that MIM related companies saw sales increasing by around 5% in 2014 following double-digit growth a year earlier. Johnson attributed the decline in growth to a cooling in demand from the North American firearm sector with some MIM companies reporting a decline of up to 40% in the first half of 2014. North American MIM sales were estimated to be in the range of $315 million to $370 million shared by some 70 companies, including 18 captive MIM operations. MIM grade metal powder shipments increased slightly to a range of 1,181 to 1,512 metric tonnes. The distribution of end user sectors based on the weight of MIM parts shipped was reported to be dominated by firearms at 28% with general industrial at 24%, medical/dental at 19%, automotive 15%, electronics 9% and miscellaneous at 5%.

Johnson reported that automotive engineers were designing more MIM parts for applications in engines, electrical systems and chassis hardware. He stated that Ford and General Motors are designing MIM parts for car models set for introduction in around five years. Other markets offering growth potential include defence, aerospace, heat sinks and thermal conducting parts, and jewellery.

www.mpif.org

European Powder Metallurgy Association launches Vision 2025 Roadmap

The European Powder Metallurgy Association (EPMA) has announced the publication of its revised Vision 2025 Powder Metallurgy Roadmap. Vision 2025 has been produced by the association and its members as a tool to aid in the promotion of the PM industry, including the Metal Injection Moulding sector, to governments, third parties and end users.

"The EPMA owes a big thank you to the members of the Steering Committee, which consisted of a number of well-known industry figures, who have worked on the EPMA's behalf to collate information from across the EPMA Members spectrum to turn this extensive project into a reality," stated Jonathan Wroe, EPMA's Executive Director. "The Vision 2025 roadmap covers many aspects, which will be very useful to third parties, such as government and funding agencies, as the content provides market overviews for the five key sectors that currently help to make up the entire PM industry, Additive Manufacturing, Hardmetals and Diamond Tools, Hot Isostatic Pressing, Metal Injection Moulding and Structural PM Components."

The Vision 2025 roadmap is available in hard copy and PDF formats.

www.epma.com

Retsch launches updated system for particle size and shape analysis

Retsch Technology GmbH, Haan, Germany, has launched the fourth generation of its Camsizer system for particle size and particle shape analysis. The Camsizer P4 features include an extended measurement range from 20 μm to 30 mm, faster cameras with higher resolution as well as a particle library for direct storage of individual particle images.

The Camsizer P4 is a compact laboratory instrument for simultaneous measurement of particle size distribution, particle shape and additional parameters of powders and granules. The system utilises dynamic image analysis through patented dual-camera technology.

www.retsch.com/camsizerp4

EPMA Powder Injection Moulding short course held in Barcelona

The European Powder Metallurgy Association's Powder Injection Moulding Short Course took place in Barcelona, Spain, from April 15–17. The intensive course featured two days of presentations by some of Europe's leading industry suppliers, researchers, academics and parts makers.

The event attracted around 50 participants and those new to PIM technology made the most of the opportunity to network and consult with industry leaders. Of note was the number of participants from the European aerospace industry and from discussions it is clear that this will be a significant growth area for PIM in Europe, particularly with regards to titanium and high temperature materials. Given the level of interest in PIM technology it is hoped that such an event can become a regular fixture in the European PIM calendar.

www.epma.com

Arburg's Marko Maetzig speaking at the EPMA PIM course

PM Review: Summer 2015 issue out now

The latest issue of *PM Review*, the magazine for the PM industry, has just been published and is available to download free of charge from www.ipmd.net.

This 80 page issue features the following articles and technical reports:

- Innovation drives Powder Metallurgy structural components forward in the automotive industry
- Conference Review: India's dynamic Powder Metallurgy industry on show at PM-15
- The gas alloying of low alloy sintered parts for improvement of mechanical properties
- Automation in PM: Increased productivity through automated handling systems in pressing technology

PM Review is available in both print (ISSN 2050-9693) and digital (ISSN 2050-9707) formats. Current and past issues are available to download free-of-charge.

www.ipmd.net/pmreview

MIM2016 conference organisers issue Call for Presentations

A Call for Presentations has been issued to solicit contributions for the MIM2016 conference technical program. Organised by the Metal Powder Industries Federation), the International Conference on the Injection Molding of Metals, Ceramics and Carbides, will take place in Irvine, California, USA, from March 7-9 2016. The focus of the technical program is innovative processes and materials.

The organisers state that innovation in different segments of Powder Injection Moulding is responsible for the rapid growth of this field. The PIM industry, comprising Metal Injection Moulding and Ceramic Injection Moulding, has estimated sales of around $1.5 billion and this could double in a span of five years.

The objective of the conference is to explore the innovations and latest accomplishments in the areas of part design, tooling, moulding, debinding and sintering of PIM parts. The conference will also focus on developments in the PIM processing of different materials including metals and alloys, ceramics and hard materials. The event is targeted at product designers, engineers, consumers, manufacturers, researchers, educators and students. All individuals with an interest in the application of Powder Injection Moulding are encouraged to attend.

The event is sponsored by the Metal Injection Molding Association (MIMA), a trade association of the Metal Powder Industries Federation (MPIF). It will be chaired by Thomas K. Houck, ARCMIM, and Stefan Joens, Elnik Systems, LLC.

MIM2015 attracts more than 130 participants

The MIM2015 International Conference on Injection Moulding of Metals, Ceramics and Carbides, took place in Tampa, Florida, from February 23 - 25. The conference, which was co-chaired by Tom Houck, ARCMIM, and Uwe Haupt, Arburg GmbH & Co KG, attracted more than 130 participants.

Speakers from the US, Europe and Asia covered all aspects of PIM, from new feedstocks through to downstream processes such as Hot Isostatic Pressing and the super-abrasive machining of MIM parts.

The Metal Injection Moulding Association's MIM conference series is the only annual international event dedicated to MIM and CIM. As well as serving as a platform for the exchange of knowledge, the conference is a highly valued networking event attended by key international materials and equipment suppliers.

www.mimaweb.org

Proto Labs adds low alloy steels to MIM portfolio

Proto Labs, Inc., based in Maple Plain, Minnesota, USA, states that product designers and engineers can now order Metal Injection Moulded low-alloy steel prototypes and low-volume production parts using its MIM rapid manufacturing service. The company has added two nickel steel materials (Catamold FN02 and FN0205) and a chrome-moly material (Catamold 42CrMo4), the MIM equivalent of 4140 steel. The new metals expand the potential applications for parts produced by Proto Labs' MIM process.

"We've had tremendous customer demand for stainless steel with MIM last year and expect the same response to our new low-alloy metals," stated Becky Cater, Proto Labs' Product Manager for MIM. "We offer many different hard and soft metals through our 3D printing and CNC machining services at Proto Labs, but nickel steel is only produced through Metal Injection Moulding. This material boost will inherently let our customers do more things in the realm of low-volume metal manufacturing."

Low-alloy steel creates strong, wear-resistant metal parts when heat-treated and is able to be to be coated in post-processing for further protection. As for applications, the low-alloy steel materials will be used heavily by the firearms industry for various gun and archery components as well as by automotive engineers for engine and transmission components and the industrial goods sector during development of hand and power tools, and door and window lock hardware, for example.

In addition to rapid prototypes, Proto Labs states that it can produce up to 5,000+ Metal Injection Moulded parts within 15 days.

In addition to offering fast turnaround low volume MIM parts, Proto Labs offers plastic injection moulding, computer numerical control (CNC) machining and Additive Manufacturing to produce parts from a wide range of materials for product designers and engineers worldwide.

www.protolabs.com

Ceramitec 2015: Organisers anticipate highest ever level of international participation

With just over six months to go before opening its gates, the organisers of Ceramitec, the world's largest international exhibition on ceramic technology, have stated that international exhibitor participation will exceed the high levels achieved at the last event in the series, held in 2012. The event takes place in Munich, Germany, from October 20-23, 2015.

To-date, exhibitors from both European and non-European countries have booked 27% more space than 2012 and Korea will take part for the first time in Ceramitec's 35-year history. "Optimism has returned to the ceramics industry. This trend is clearly indicated by the growth of the exhibition space of Ceramitec 2015. The international growth is also noticeable compared to the 2012 registration period. In 2015, almost 60% of the exhibitors will come from abroad," stated the organisers.

A growth rate of 43% has been given for the Technical Ceramics area, which traditionally attracts a high level of participation from specialists in Ceramic Injection Moulding. It was also stated that the Powder Metallurgy area has recorded growth of 28%.

"The positive development of Ceramitec is reflecting the market situation and the even greater international mix proves that the ceramics industry sees Ceramitec as an international key trade show. In view of the forthcoming event, this makes me more than confident," stated Gerhard Gerritzen, Deputy Managing Director of Messe München.

PIM International will once again be exhibiting at Ceramitec, with additional distribution of our September 2015 issue (Vol. 9 No. 3) at key locations in the exhibition hall. To advertise in this show issue, which will also be distributed at the Euro PM2015 event, contact Jon Craxford, jon@inovar-communications.com.

www.ceramitec.de

Ceramitec 2012 proved to be a busy exhibition for Ceramic Injection Moulding related exhibitors, who ranged from materials and equipment suppliers to research centres, consultants and parts makers. The event also features a busy Powder Metallurgy area

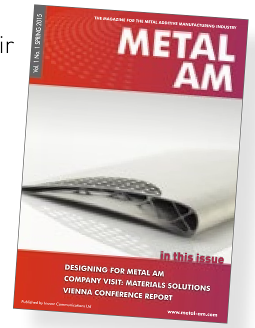
Launch issue of *Metal Additive Manufacturing* magazine now available to download

The launch issue of *Metal Additive Manufacturing*, the new quarterly magazine for the metal Additive Manufacturing industry, is now available to download from the publication's dedicated website, www.metal-am.com.

Available in both print (ISSN 2057-3014) and digital (ISSN 2055-7183) formats, *Metal Additive Manufacturing* brings together industry news and articles on technical and commercial developments in the industry. The publication of this new magazine follows the successful launch of the www.metal-am.com website in May 2014.

The 64 page launch issue includes a report on a recent visit to leading European metal AM parts producer Materials Solutions, based in Worcester, UK. Materials Solutions is a key supplier to the aerospace and high performance motorsport industries. In our exclusive report the company's founder and Managing Director, Carl Brancher, shares his thoughts on the current status of the metal Additive Manufacturing industry and the opportunities and challenges ahead.

Also featured in this issue is an extensive report on component design considerations for powder bed fusion technologies. As Tim Richter, RSC Engineering GmbH, Germany, explains, this technology has the potential to fundamentally change the design process and appearance of new products. Designers must, however, be aware of all design considerations to maximise the potential of their products.



Jon Craxford, Sales Director at Inovar Communications, a publishing house with over twelve years of experience in the metal powder processing industries, commented, "We are delighted with the support that we have received from industry suppliers, component manufacturers, trade organisations and international industry events."

The print edition of *Metal Additive Manufacturing* is available by subscription. The launch issue is also being distributed at AMPM 2015 (May 18-20, San Diego, USA), RAPID 2015 (May 18-21, Long Beach, USA), and the Rapid.Tech exhibition (June 10-11, Erfurt, Germany).

www.metal-am.com

Arburg Technology Days 2015: Experts meet in Lossburg

Almost 6,000 invited guests attended the Arburg Technology Days 2015 event in Lossburg, Germany, from March 11 – 14, 2015, in order to gain a detailed insight into industry trends and to see highlights of the Arburg's latest injection moulding technology. This year's event had the theme of production-efficient processing technologies.

"Once again this year we have put together a very interesting range of technologies and services for our international guests, presenting our innovative and production-efficient solutions and offering an insight into the future of efficient plastic parts production," stated Michael Hehl, Managing Partner and spokesperson for the Arburg Management Team.

"As every year, we welcomed several thousands of visitors from all over the world. This is because there is no comparable event all over the world and because we can attend our customers in a more intensive and individual way, compared to the trade fairs." Around 45% of visitors travelled from abroad, with large delegations from the US and China.

Micro parts production was highlighted with a special micro production cell built around an electric Allrounder 270 A operated with the new Euromap size 5 micro-injection unit. Together with a linear Multilift H 3+1 robotic system, this formed a flexible system solution for the reproducible production of micro components, in this case micro counter wheels weighing just 0.004 g. The new micro-injection unit combines the precise regulation of short strokes with high filling dynamics.

www.arburg.com

Management changes at Bosch Mahle Turbo Systems

Bosch Mahle Turbo Systems, a joint venture between Bosch and MAHLE with headquarters in Stuttgart, Germany, has announced changes to its management team. Dr Roger Busch and Alexander Kutsch will be replacing the company's previous Managing Directors, Dr Martin Knopf and Dr Andreas Prang.

Dr Busch has been appointed Managing Director, Development, Sales, Finances and IT at Bosch Mahle Turbo Systems and has taken over from Dr Knopf who left the company on January 31, 2015. Roger Busch has many years of experience within the Bosch Group. Since he started in 2001 he has assumed various responsibilities, most recently as lead developer in the Gasoline Systems division.

Kutsch will be introduced as the new Managing Director Technology, Quality, Purchasing, HR and Production. After many years of international experience in the MAHLE Group, Kutsch, who is currently Managing Director of MAHLE Filter Systems (India) Ltd., will assume his new position on June 1, 2015. Dr Prang, who previously held the position, left the company on January 31, 2015. Michael Bernd will handle his duties until Kutsch takes over in the middle of the year. Before taking on his current function in the MAHLE Group within the Filtration and Engine Peripherals (Europe) business unit in July 2014, Michael Bernd held key positions at various well-known automotive suppliers.

Bosch Mahle Turbo Systems was founded in 2008 as a joint venture between Bosch and MAHLE. The joint venture develops, manufactures and distributes exhaust gas turbochargers for passenger cars, commercial vehicles and off-highway applications, as well as for stationary engines.

www.bmturbosystems.com

Indo-MIM receives 'Best Supplier Award' from Danfoss

Indo-US MIM Tec Pvt. Ltd, one of the world's largest MIM producers based in Hoskote, Bangalore, India, recently received a Best Supplier Award 2015 from Danfoss, Denmark, under the category of Value Addition/ Value Engineering (VA/VE) and for Indo-MIM's efforts in developing various critical components through integrated technology and product innovation.

Dan Rohde, Global Procurement Director, Refrigeration & Air Conditioning Controls Division, and Prashant Yardi, Global Category Manager, presented the award to Krishna Chivukula Jr., CEO, Indo-MIM for pro-active ideas on VA/VE resulting in mutual business impacts. Cutting edge technology and new designs resulted in cost savings for Danfoss.

www.indo-mim.com

Peter Moelgg appointed President of Engineering at GKN Automotive

Peter Moelgg has been appointed to the position of President of Engineering GKN Automotive, covering the GKN Driveline and GKN Powder Metallurgy divisions. GKN Driveline is the world's leading supplier of automotive driveline systems and solutions, while GKN Powder Metallurgy produces precision powder metal products for engines, chassis, transmissions and driveline systems.

Moelgg will head engineering across the two divisions, leveraging synergies to identify and bring to market innovative, leading technologies for GKN's expansive automotive customer base. He joined GKN in 1979 and has held a number of senior engineering and general management positions in GKN Driveline and GKN Powder Metallurgy, most recently as President Europe and Asia Pacific for GKN Sinter Metals. He has established a GKN Automotive Technology Council to help develop new solutions.

Moelgg stated, "Technology is at the heart of GKN and is crucial to our strategy to develop the innovative, intelligent electric drives and all-wheel drive systems of the future, whilst also maintaining our leadership in conventional drivelines."

"I am extremely excited by this new role; GKN has a wealth of engineering expertise and experience to draw on from across the Driveline and Powder Metallurgy divisions. I want to ensure the full value of technology across our automotive businesses is rapidly developed to bring market leading technology to our customers."

Andrew Reynolds Smith, Chief Executive Officer of GKN Automotive, added, "Car manufacturers are increasingly under pressure to deliver efficiency, as well as performance which makes cars great to drive. Intelligent drivelines and lighter vehicle components and systems are helping to achieve this goal. We are working hard to develop the best technologies for today's markets and also committing significant investment in advanced technologies for the future."

Moelgg will be based in Bruneck, Italy. He replaces Rob Rickell in the role, who has moved to become GKN President, Group Technology with a remit to oversee technology development and innovation across the GKN Group.

The March 2015 issue of *PIM International* featured the report "GKN Sinter Metals: Process automation enables growth in automotive applications," covering developments at GKN's MIM operation in Bad Langensalza. Download your free PDF copy from www.pim-international.com

www.gkn.com

Enhanced abrasion resistance for injection moulding screws and barrels

Plasticising units such as screw and barrel materials used for injection moulding and extrusion are subject to increased wear through the processing of filled compounds where the compound can have a filler loading of 50% or higher. In automotive manufacturing, for example, carbon fibre-reinforced composites are in growing demand as light-weighting alternatives to metals. In under-hood auto applications, compounds heavily filled with glass and minerals are now widely used. A similar challenge is posed by the growing demand for highly filled halogen-free flame retardant (HFFR) compounds for wire and cable. Processors are commonly using calcium carbonate filler at 50% loadings and the growth of Metal Injection Moulding, where powder loading is often in excess of 60%, poses yet another abrasion challenge.

Nordson Xaloy Inc of New Castle, Pennsylvania, USA, has introduced two alloys which the company states can improve the abrasion resistance of plasticising units subject to wear from filled compounds and thereby extend the working life of the units. The company's X-8000™ is a nickel-base alloy with high tungsten carbide content used for screw encapsulation. Nordson applies this alloy to the entire screw geometry using a high velocity oxy-fuel (HVOF) coating process; it then fuses the alloy to the base metal of the screw in a two-step method that forms a metallurgical bond, rather than the purely mechanical bond formed by standard HVOF coatings. In addition, X8000 coating is double the thickness of other HVOF applied coatings, 0.50 mm versus 0.25 mm. The high nickel content provides enhanced corrosion resistance.

X-800® is also a nickel-based alloy with tungsten carbide and is used for barrel inlay, which the company states is more wear-resistant than iron-based, iron-chromium and nickel-cobalt alloys, providing exceptional abrasion and corrosion resistance with highly filled materials and high-temperature engineering polymers.

www.xaloy.com

Screw with competitive carbide coating (left) shows poor adhesion and chipping, while screw with metallurgically bonded Nordson's Xaloy X-8000™ coating (right) exhibits no chipping

Leatherman introduces wearable MIM tool bracelet

Metal Injection Moulding is used extensively in the production of the Leatherman Tread multi-tool and watch system

The Leatherman Tool Group, based in Portland, Oregon, USA, will debut its new multi-tool 'Leatherman Tread' bracelet this summer. Designed to be worn on the wrist, this new wearable tool is made from high strength, corrosion resistant 17-4 stainless steel using Metal Injection Moulding to produce the individual links. Each complex shaped link on the band includes two to three functional tools for a total of 25 usable features such as box wrenches and screwdrivers. The bracelet was created to be fully customisable with slotted fasteners, so the user can rearrange links, add new ones, or adjust for wrist size. The clasp is also functional, with a bottle opener and #2 square drive. Other link tools include a cutting hook, hex drives, screwdrivers, box wrenches and a carbide glass breaker. The Tread bracelets will be available in a stainless steel finish at a price of around $150, and a black Diamond-Like Carbon (DLC) finish will cost around $200.

Leatherman President Ben Rivera stated that the idea for the multi-tool bracelet originated on a trip to Disneyland with his family. Rivera said "I was stopped at the security gate for carrying a knife, when what they had actually seen was my Skeletool. I was unwilling to give it up, so they made me take it all the way back to my hotel room. I knew there had to be another way to carry my tools with me that would be accepted by security." When he returned from his trip, Rivera, who began his tenure at Leatherman Tool Group 24 years ago as an engineer, began by wearing a bike chain bracelet to see how it would feel. As his thoughts took shape, he brought his idea to the engineers at Leatherman who helped fast track his plans.

"I began wearing prototypes myself to test comfort and usability and to ask for feedback," stated Rivera. "Folks immediately associated the bracelet design with a watch and asked, where's the watch? We decided to make a timepiece an optional part of the Tread." A version of the Tread bracelet that includes a watch will be available later this year. The Leatherman Tread™ QM1 will feature a unique Leatherman-designed and Swiss-made timepiece with precision quartz movement. A shock resistant sapphire crystal ensures scratch resistance and the curved watch limits reflection. The tread watches will cost $500 for stainless steel and $600 for black DLC.

www.leatherman.com

MIM technology transferred to the 3D printing of aluminium and stainless steel

A small group of engineers in Orange, Massachusetts, USA, called the Sinterhard Team is organising a 'Kickstarter' company to raise funds and gain support for the manufacture of industrial components using new metal filled PLA (Polylactic Acid) and ABS (Acrylonitrile, Butadiene Styrene) plastic filaments containing either 316 stainless steel or aluminium powders. These filaments have a 20% plastic and 80% metal powder loading. They are then processed into parts by a 3D metal filament printer following which the plastic is removed from the printed part by a debinding process essentially the same as that used in MIM or CIM. After removal of the plastic the metal is heated to 'near-full density' in a sintering furnace.

Bill Novacs, who heads up the Sinterhard Team, states that the process is essentially identical to the existing MIM process, except that the 3D filament printer replaces the plastic injection moulding machine and the mould, and with the Sinterhard metal filled filaments replacing MIM feedstock.

"In selecting 316 stainless steel and aluminium powders, we are starting with two of the most common metals that are in use making parts with the current industrial MIM process. They have a moderate sinter temperature (316 stainless steel) and a low sinter temperature (aluminium) as a starting point. These metals cover a large range in commercial applications and are available in the fine mesh size we need to insure a high quality 3D printed part," stated Novacs.

www.kickstarter.com

MPIF announces Distinguished Service to PM award winners

The Metal Powder Industries Federation (MPIF) Awards Committee has announced the recipients of its 2015 MPIF Distinguished Service to Powder Metallurgy Award. The award recognises individuals who have actively served the North American Powder Metallurgy industry for at least 25 years and, in the minds of their peers, deserve special recognition.

The awards will be presented during an industry Luncheon taking place on May 18 at the POWDERMET2015 conference in San Diego, USA. The 2015 Distinguished Service Award recipients are:

- François Chagnon *(Formerly of Rio Tinto Metal Powders)*
- Robert J Dowding *US Army Research Laboratory*
- Ulf Engström *Höganäs China Co. Ltd.*
- Howard A. Kuhn *The ExOne Company*
- Thomas J Miller *Chicago Powdered Metal Products Co.*
- César Molins, Jr *AMES S.A.*
- James H Neill *CM Furnaces, Inc.*
- Craig C Paullin *PSM Industries, Inc.*
- Thomas W Pelletiers *SCM Metal Products, Inc.*
- Dennis Poor *Kittyhawk Products*
- Prasan Samal *(formerly of North American Höganäs, Inc.)*
- Blaine Stebick *Phoenix Sintered Metals, LLC*
- S.K. Tam *Ormco Corporation*
- John von Arx *NetShape Technologies, Inc.*

Iver Anderson named TMS Fellow 2015

Iver E Anderson, who leads the Critical Materials Institute Industry Council and efforts in Technology Deployment at Ames Laboratory (USDOE), was recently named a 2015 Fellow of The Minerals, Metals & Materials Society (TMS).

Anderson is one of six new Society members who have earned the highest award bestowed by TMS, which recognises members for their outstanding contributions to the practice of metallurgy, materials science, and technology. Anderson was specifically recognised for his inventiveness that led to lead-free solder used in all electronic devices and for seminal contributions to the gas atomisation of metallic and polymeric materials, PM technology, and rapid solidification processing of a wide variety of materials. Anderson is also Adjunct Professor at Iowa State University.

www.tms.org

HC Starck reports increased sales despite weak market development

The HC Starck Group, headquartered in Munich, Germany, has reported that in 2014 the company increased its sales volume to €785.9 million, up from €703.9 million in 2013.

"The increase in sales was also supported by our strategic growth projects in Asia: the tungsten joint ventures in China and Vietnam. That helped us grow significantly our tungsten powder business, and gain large market shares especially in Asia," stated Andreas Meier, CEO of HC Starck. "Overall, though, 2014 was shaped by the difficult economic situation in our global core markets, which hurt the profitability of the business."

Sales in the tungsten powder division increased by more than €75 million in 2014, bolstered by new customers and market share gains. In addition, the tungsten joint venture in China led to a significant sales-volume increase. The tungsten component business also saw a clear increase in sales volume, in particular thanks to the competitive cost structure at the division's Chinese manufacturing site.

In the tantalum and niobium powder business, HC Starck reported no increase in demand. But despite this difficult market environment, the company was able to gain market shares for tantalum powders and reinforce its competitive position.

In the Surface Technology and Ceramic Powders division, HC Starck saw a double-digit percentage increase in sales. In particular, the thermal spray powder business benefited from increased demand in the United States and several new products and customers. The products sold under the names Amperit and Ampersint are important materials for energy production, medical technology as well as the oil and gas industry and Metal Injection Moulding.

Despite the difficult situation in 2014, HC Starck managed to increase its investments up to around €40 million. The major part of the budget was spent for the construction of the production facilities of the new tungsten joint venture in Vietnam, into the German production sites and into the further expansion of the tungsten joint venture in China.

Research and development focused on projects to increase the yield in processing secondary materials and by-products, to continuously improve the quality of high-capacity tantalum and niobium powders, and to develop special tungsten carbides for the Asian market. Additionally, HC Starck signed a development contract with Rapid Prototype and Manufacturing (rp+m), a US Additive Manufacturing specialist.

www.hcstarck.com

Production parameters affecting the impact toughness of MIM parts

Whilst a substantial number of technical papers have investigated the influence of sintering parameters and powder loading on the mechanical properties of MIM components, the effects of the different aspects of the injection moulding steps on properties such as impact toughness has been less well reported.

P Pachauri and Md. Hamiuddin at the College of Engineering & Technology, Aligarh, UP, India, have undertaken research to optimise the moulding parameters which would simultaneously satisfy the requirements for quality control of MIM parts in the green state in order to attain the desired impact toughness in the sintered parts. The authors reported on their work in the *Int. Journal of Advanced Materials and Metallurgical Engineering* (Vol. 1, No. 1, 2015, pp-1-11).

The controlled parameters used for optimisation in this research include injection pressure, injection temperature, mould temperature, holding pressure and holding time, injection speed, powder loading and cooling time. These parameters have been optimised using analysis of variance (ANOVA) for signal to noise ratios obtained in experiments performed by following a Taguchi L_{27} orthogonal array.

Results show that the injection pressure, mould temperature and powder loading are highly significant factors with reference to the impact toughness, while the injection temperature, injection speed, holding pressure, holding time, cooling time and the interaction of injection pressure and mould temperature do not show significant effect at 95% confidence level.

Impact test pieces were produced in the form of injection moulded unnotched bars in accordance with MPIF Standard 50 and ASTM Standard E8-98 using 316L stainless steel powder mixed with a binder comprising polyethylene glycol (PEG), polymethyl methacrylate (PMMA) and stearic acid (SA). Three types of feedstock with fine weight control and homogeneous mixing were used for the twenty-seven runs which were divided into three sets of nine runs each with the level of powder loading constant. The moulded test bars were debound first by solvent debinding followed by thermal debinding at 350°C in a vacuum furnace to remove the PMMA and stearic acid. The debound parts were then pre-sintered to 900°C followed by final sintering under vacuum at 1360°C.

From the experiments undertaken it was found the impact toughness has a maximum value when injection moulding pressure for the 316L feedstock investigated is 55 MPa along with mould temperature of 55°C and powder loading of 61.5 vol%. The level average response required for the analysis of the trend of performance characteristic with respect to the variation of the factors under study is shown in Fig.1 and the interaction plot of injection pressure, mould temperature and powder loading in Fig. 2. It was also found that the average impact energy absorbed obtained in the research is within the predicted 95% confidence value as can be seen in Table 1.

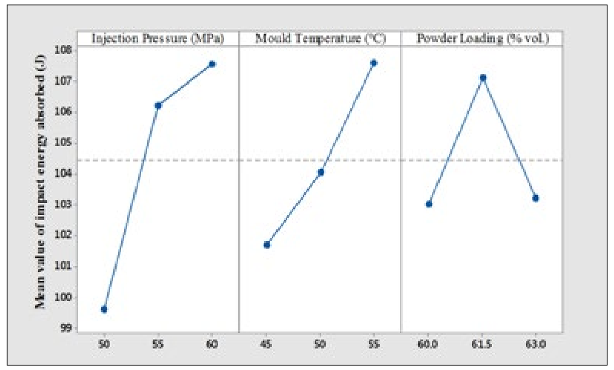


Fig. 1 Main effects plot for mean values of impact energy absorbed (From the paper 'Optimization of Injection Moulding Process Parameters in MIM for Impact Toughness of Sintered Parts)

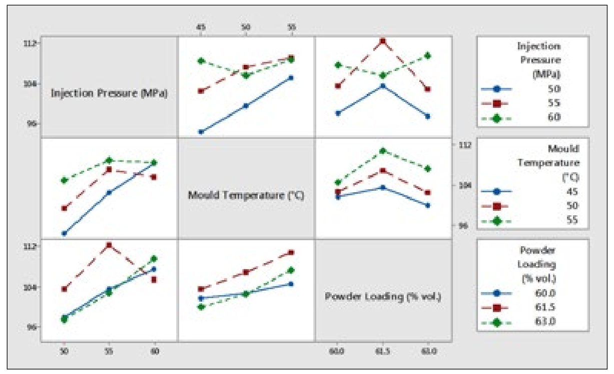


Fig. 2 Interaction plot of injection pressure, mould temperature and powder loading (From the paper 'Optimization of Injection Moulding Process Parameters in MIM for Impact Toughness of Sintered Parts)

Characteristic	Replication at optimum process parameters					Average	Minitab predicted value
	R1	R2	R3	R4	R5		
Impact energy absorbed (J)	110	112	111	114	112	111.8	113.36

Table 1 Results of confirmation experiments

Powder Technology course to run at Lund University

A three day course on Powder Technology in Pharma, Food, Chemistry and Metallurgy is scheduled to take place at Sweden's Lund University, September 9-11, 2015. The aim of the course is to provide participants with a better understanding of powder products and processes and to supply tools to stimulate new ideas for development and improvement of powder products and processes.

The course format includes round table discussions focusing on specific themes such as rheology, powder characterisation, granulation, agglomeration and processing of metal powders. The course will focus on all powders used industrially, with a special module focusing on metallic powders and their applications.

The metallic powders and their applications programme discusses methods for producing metal powders, microstructure control and powder preparation, shaping and consolidation, including sintering. HIP and full density processing is covered along with the characterisation of powder products and material properties.

luvit.ced.lu.se

USD Formteiltechnik GmbH and USD Powder GmbH: Playing an increasing part in MIM technology

USD Formteiltechnik GmbH and USD Powder GmbH may not be widely known names in the industry, but seen together these companies are not only significant buyers of MIM parts, but also an increasingly important force in the world of MIM powder production. Dr Georg Schlieper visited the two companies in Meinerzhagen, a small town in the woody hills of the Sauerland region of Germany, and reports for *PIM International* on their history, business activities and ambitious plans for the future.

The rural area of Sauerland is perfect for outdoor activities such as hiking and biking, yet it is also home to a number of metalworking businesses and industrial concerns. The steep hills and stony soils left little room for agriculture, so technical skills were developed by the population at the start of the industrial revolution. Numerous factories were established and many of these are still successful today.

Christian Kosak, one of three Managing Directors of USD Formteiltechnik GmbH, explained that his father, Jürgen Kosak, had established the company in 1977. Initially he started with nothing more than a typewriter and stationery, with which he began to contact his first customers. From the start his focus was on the marketing of steel components. The manufacturing technologies covered in the early years of the business were primarily die forging, sand casting and investment casting as the many family-owned businesses in the area manufactured components by these processes. USD's first customers were manufacturers of valves and pumps for power plants.

The company's business philosophy has always been technology-oriented. The range of metalworking processes represented by USD gradually expanded to include die casting, precision casting, stamping, turning and milling. By learning about the strengths and weaknesses of the various parts

Fig. 1 USD's headquarters in Meinerzhagen, Germany

Fig. 2 The modern warehouse at USD

manufacturing technologies, the company developed specialist knowledge that allowed it to offer the most cost-effective technology for the production of a customer's part.

In 1985 the first sintered products were delivered. Since this time the portion of Powder Metallurgy products in USD's portfolio has steadily increased. In order to meet the delivery requirements of customers at any time, a warehouse was purchased in the same year. In 2000 the first MIM parts were developed for producers of locks and fittings. USD supports its customer base in selecting the most suitable process for a given application, as well as helping with the design requirements for a given processing technology.

The company headquarters was moved to the current building in 1997 (Fig. 1) and in 2013 the existing storage capacity of 1500 m² was extended with a newly constructed warehouse with 3000 m² of floor space (Fig. 2). A sophisticated logistics system is installed, ensuring that products can be delivered efficiently and on time. High-bay storage and an advanced IT system enables USD to ensure inventories of critical stock is available to meet customer requirements. Deliveries can be in accordance with fixed schedules, following special orders, or via the application of a Kanban-based system. Delivery schedules, individually agreed with each customer, are effective worldwide.

Focus on quality management

In 2014 substantial investments were made in USD's quality assurance department and quality assurance is today a major, and increasing, part of USD's service. The company takes a mediating position between parts manufacturers and end-users. An important aspect of the business' philosophy is that, although no products are manufactured in-house, the company takes full responsibility for the quality of the products it distributes. As a consequence, a great deal of quality inspection work is carried out at USD. This not only covers part dimensions, but also includes metallographic inspection as appropriate. A view of the quality department at USD is shown in Fig. 3. The company's quality management system has been certified according to ISO 9001 since 1998.

In 2013 the company received the Fachmetall PM Qualification Award for its outstanding services to the industry for introducing Powder Metallurgy technology in new application areas, as well as for its in-depth quality assurance work relating to both conventional PM and also MIM components. Out of USD's workforce of 53, every fifth employee works in quality management (Fig. 4).

Over the years, strong relationships have been established with specialist parts suppliers from all over the world. Today USD is a truly global company purchasing parts from suppliers in 17 countries. The company sells these parts to customers in 26 countries in Europe, North America and Asia under the USD brand, which is a registered trademark.

Fig. 3 The quality assurance department at USD

Fig. 4 The USD team in the dispatch area

Despite being present on the international market, USD's expertise remains concentrated at its headquarters in Meinerzhagen. The Executive Board of USD Formteiltechnik GmbH comprises Jürgen Kosak and his sons Christian and Sebastian Kosak. USD still prefers family-owned businesses as suppliers because, stated the company, it seems more effective to establish long term person-to-person relationships with family-owned businesses rather than with bigger companies. "Some of USD's suppliers deliver 70-80% of their production to us," Christian Kosak told *PIM International*. "This creates strong ties and an interdependence that even leads to mutual decisions about investments. These relationships often last for decades."

Business strategy

USD's customers and products can be found in almost all industrial sectors with the exception of the aerospace industry. Thanks to its wide range of resources, USD is able to provide solutions for most applications. Components for agricultural equipment, precision parts for consumer products, and the automotive sector are just a few examples; the variety of products is extremely diverse. Part weights range from 0.006 g to more than 1 metric ton, with the total weight of products distributed through the Meinerzhagen facility amounting to 9,800 tons.

"USD actively approaches customers, offering in-house workshops about the various manufacturing technologies for metal components, in particular about PM and MIM technology..."

Turnover in 2014 was €35 million. The range of materials is as wide as the range of applications and includes low and high alloy steels, stainless steels, tool steels, aluminium, titanium, copper, brass, bronze and many more.

Specialist engineers with expertise in each processing technology provide expert knowledge for the selection of the best solution, both technically and economically, to a given application. USD actively approaches customers, offering in-house workshops about the various manufacturing technologies for metal components, in particular about PM and MIM technology, including design guidelines, materials, dimensional tolerances, surface treatments and heat treatment. Thorsten Klein, Head of the PM and MIM sector, told *PIM International*, "It cannot be overemphasised how important these activities are for the business relationship between customer and supplier. In principle, USD does what all manufacturing companies do for marketing, but USD has no production facilities and is free to choose the technology that is best suited for the application. This is a service that our customers appreciate."

In some instances a customer's new product may sell much better than initially expected. In this

Fig. 5 MIM parts used in the furniture industry

Fig. 6 Selection of various MIM parts supplied through USD

situation USD investigates on behalf of the customer if another technology is more economical than the original one, given the change in production volumes. In many cases PM and MIM offer clear advantages with increasing volumes. As a result of such pro-active collaboration, USD stated that its contact with a company's design engineers is often as close as with its purchasing department.

MIM products

According to Klein, USD holds a strong position in relation to MIM parts for manufacturers of industrial machinery as MIM parts often replace milled parts or investment castings in this sector. Other MIM markets served by USD are medical technology, photographic equipment, binoculars, luxury consumer goods and the food processing industry. MIM parts handled by USD range from 0.006 to 140 g and delivery volumes start as low as 5,000 parts per year.

Two examples of MIM products used in the furniture industry are shown in Fig. 5. The material is a modified 100Cr6 (Fe-1.5 Cr-1 C) heat-treated to 60 HRC and chromium plated.

More examples of MIM products distributed by USD Formteiltechnik GmbH are shown in Fig. 6. Among these are two mobile phone parts (1, 2) made from 17-4PH and weighing 0.058 and 0.185 g, a pair of pliers for laparoscopic surgery (3) made from 316L, two parts for medical devices (4, 5) from 316L weighing 0.006 and 0.171 g, and a shaft for a motor (6) made from 17-4PH and hardened.

"Converting a product from another technology to MIM requires high technical competence and is associated with a great deal of work and investment in tooling," commented Klein. "If in spite of these impediments a conversion is successful both technically and economically, the customer will appreciate the benefits of our services and extend the relationship with USD."

From structural parts to iPowder®

In 2011, initial plans were prepared to become involved in the production of metal powders for MIM. An innovative gas-water atomising process had been developed that appeared to have the potential to enable the production of metal powders for MIM at a lower cost than existing processes. The technology was still at an early stage of development, but the powders produced with the prototype equipment were extremely clean and fine enough for MIM. A strategic alliance with a Chinese company was formed with the goal of establishing a metal powder production facility in Asia. USD Powder GmbH was formed in 2014 as the central base for technical sales and distribution to consumers outside of China and India. Shareholders in USD Powder GmbH are USD Formteiltechnik and Thorsten Klein. Klein, along with Christian and Sebastian Kosak, are the company's General Managers (Fig. 7). These newly developed metal powders are marketed under the registered trade mark iPowder®.

Atomising equipment from a German manufacturer was transferred to the partner in China. Tests with various nozzle geometries were carried out over more than a year to optimise the hardware and process parameters were determined using high-speed cameras until the necessary foundations for mass production had been prepared.

The gas-water combined atomising process used at USD Powder starts with a melt of the required alloy composition in an electrically heated tundish (Fig. 8). Before leaving the tundish through a hole in the bottom, any possible slag is effectively removed from the melt by passing it through a ceramic filter. This ensures, stated Klein, that the powder has unsurpassed cleanliness and MIM parts that are made from the powder are free from non-metallic inclusions.

The melt stream leaving the tundish is first atomised by gas into relatively coarse droplets. So far, the process is identical to established gas atomisation processes. Before the melt droplets completely solidify, however, a second atomising stage follows which operates with water and the droplets are further disintegrated. Water, with its higher mass and heat capacity compared to gas, is very effective in reducing powder particle size. The powders produced using this two-stage process have a high proportion of spherical particles with a D50 value between 8 and 9 microns. An example is shown in Fig. 9.

The most common alloys produced by USD Powder are 17-4PH, 316L and Fe2Ni. All powder grades are prealloyed. Besides the average particle size D50, tap densities are specified within close limits and most powder grades are available with at least two different tap densities (Table 1). The reason, as pointed out by Klein, is that polyacetal based MIM binders require higher tap densities than wax based binder systems. The particle size distribution of iPowder® 17-4PH (8) is shown in Fig. 10.

Fig. 7 The young management team of USD Powder (left to right): Sebastian Kosak, Thorsten Klein and Christian Kosak

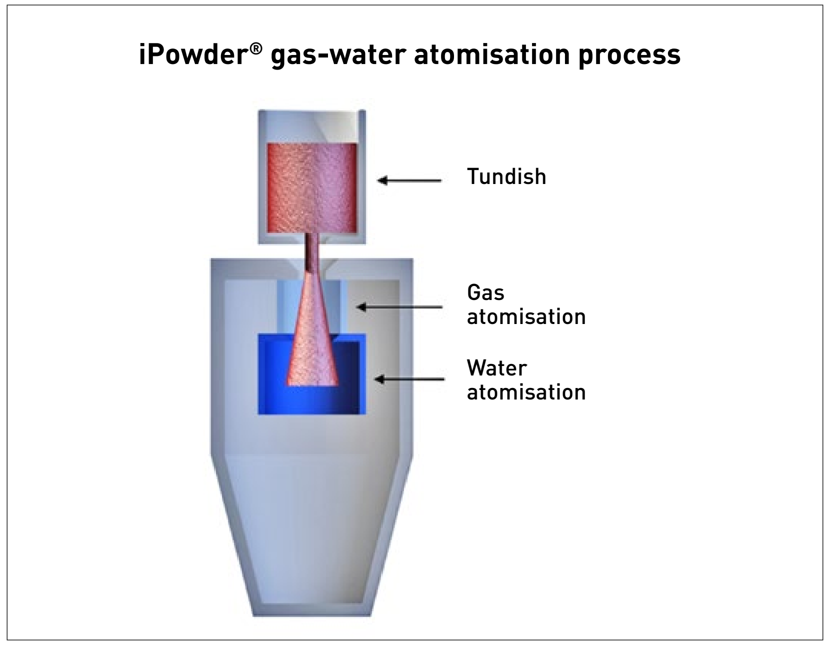


Fig. 8 Gas-water combined atomisation schematic

Thanks to lower gas consumption, which is one of the major cost contributions in gas atomised powders, USD Powder states that the price of iPowder® is comparable to water atomised powders. Another factor for improved cost competitiveness is the high level of efficiency of the process for production of the required powder

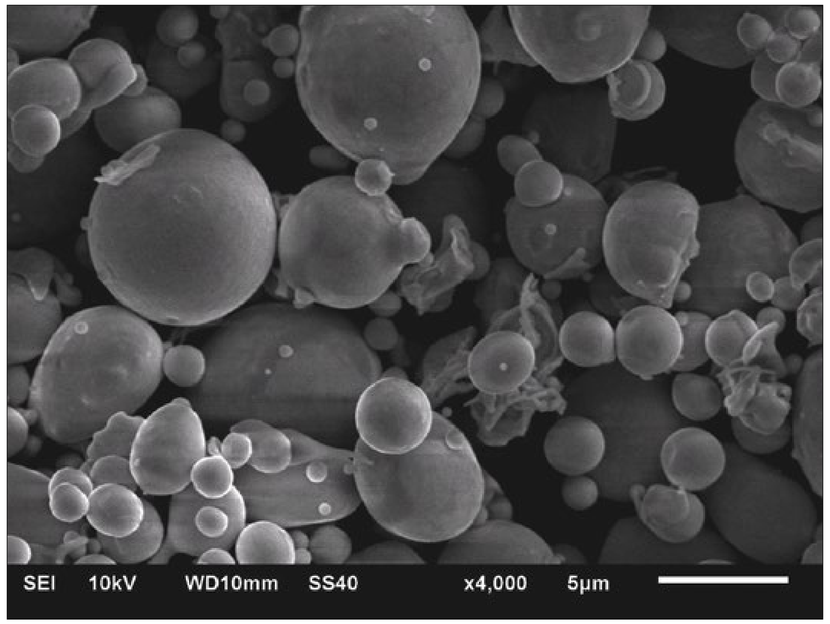


Fig. 9 Gas-water atomised 17-4PH powder (SEM)

Material	D50	Tap Density
iPowder® 304L(8)	8-9 µm	4.75 - 4.90 g/cm³
iPowder® 304L(D)	8-9 µm	4.50 - 4.60 g/cm³
iPowder® 316L(6)	6-7 µm	4.60 - 4.70 g/cm³
iPowder® 316L(8)	8-9 µm	4.75 - 4.90 g/cm³
iPowder® 316L(D)	8-9 µm	4.50 - 4.60 g/cm³
iPowder® 17-4PH(8)	8-9 µm	4.65 - 4.80 g/cm³
iPowder® 17-4PH(D)	8-9 µm	4.40 - 4.50 g/cm³
iPowder® 4140(8)	8-9 µm	4.50 - 4.70 g/cm³
iPowder® 4140(D)	8-9 µm	4.30 - 4.50 g/cm³
iPowder® 420W(8)	8-9 µm	4.60 - 4.80 g/cm³
iPowder® 430L(8)	8-9 µm	4.50 - 4.70 g/cm³
iPowder® 440C-3Nb(8)	8-9 µm	4.50 - 4.70 g/cm³
iPowder® 4J42(8)	8-9 µm	4.70 - 4.90 g/cm³
iPowder® 8620(D)	9-11 µm	4.40 - 4.60 g/cm³
iPowder® HK30(8)	8-9 µm	4.50 - 4.70 g/cm³
iPowder® Kovar(8)	8-9 µm	4.80 - 5.00 g/cm³
iPowder® Fe2Ni(8)	8-9 µm	4.60 - 4.80 g/cm³
iPowder® Fe6.5SiCr(8)	8-9 µm	3.90 - 4.10 g/cm³
iPowder® Fe6.5SiCr(15)	13-15 µm	4.10 - 4.30 g/cm³
iPowder® FePBNbCr(6)	6-7 µm	3.90 - 4.10 g/cm³
iPowder® FePBNbCr(8)	8-9 µm	4.10 - 4.30 g/cm³

Table 1 USD iPowder® grades

fractions. The present capacity of 2000 tons per year will be doubled this year, with long-term capacity planned to be at least 10,000 tons per year.

The oxygen content of the powder is important for alloys with a controlled carbon content. Oxygen combines with carbon forming carbon monoxide, which evaporates as a gas. The carbon content of the sintered alloy is therefore reduced by the oxygen content of the powder. USD Powder states that the oxygen content of water atomised powders is typically 3500 to 4000 ppm. USD's gas-water atomised powders usually contain approximately 3000 ppm oxygen. For alloys with carbon control requirements, the process can be modified by customer request to reach an oxygen content of only 500 to 800 ppm.

USD Powder is the sole distributor of its metal powders to consumers in all parts of the world. Although binder compositions and feedstock preparation is the responsibility of the customer, USD Powder provides recommendations with the powders regarding feedstock compositions and debinding and sintering parameters. MIM parts producers who do not wish to install their own feedstock preparation capability can purchase ready-made feedstocks based on iPowder® from their preferred feedstock suppliers.

With its powder atomising facility USD Powder GmbH is in a strong position to design MIM alloys, or to modify carbon and oxygen content, according to customer requirements. An example is a unique copper-nickel alloy CuNi 75/25 which as a pre-alloyed powder is only available from USD Powder (Fig. 11).

Material safety data sheets are provided with all powders, containing information about safe handling and storage, health hazards and protective measures as well as actions in case of an accident or fire etc. Registration under the European Union's REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals) will become compulsory in 2018 and USD Powder GmbH already provides its customers with all required documents.

Outlook

"Introducing a new powder supplier in a MIM plant is always a challenging and time-consuming process," Klein told *PIM International*. "If a customer is interested, they will start trial runs with small quantities and gradually increase the orders. Months may elapse before the deliveries reach an economically attractive level. This requires significant financial stamina from a supplier." USD Powder states that customers have also successfully blended iPowder® with gas atomised powders to reduce costs.

The market for fine metal powders is expanding, not only with the growing MIM industry, but also with emerging metal Additive Manufacturing technology. This leaves room in the market for various powder production technologies. USD Powder GmbH has secured a strong position among the long-established providers of fine metal powders and will continue to serve the industry in the years to come.

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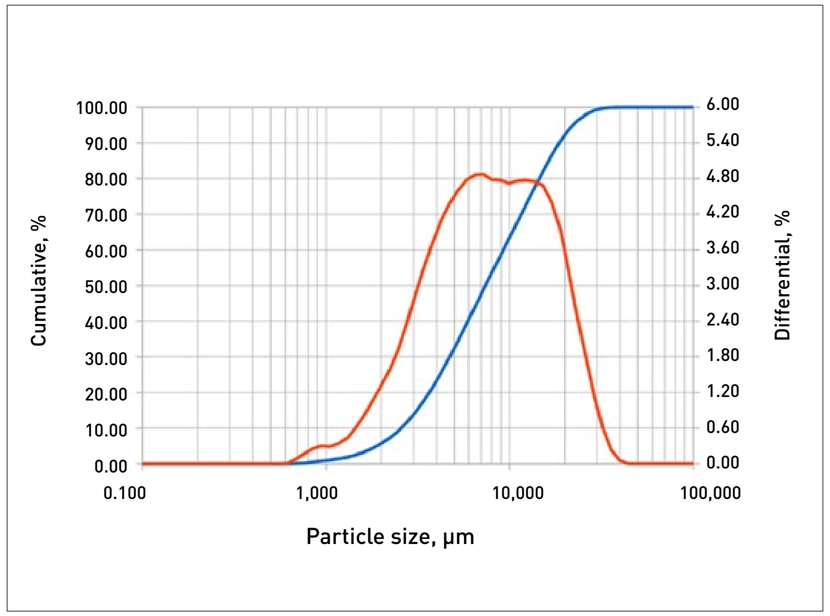

Fig. 10 Particle size distribution of iPowder® 17-4PH(8)

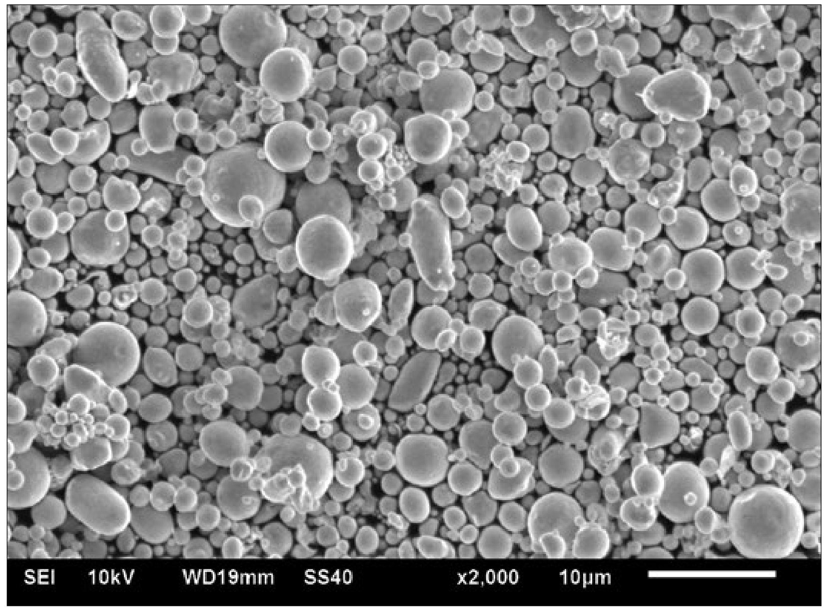

Fig. 11 Gas-water atomised iPowder® CuNi 75/25 (SEM)

UCLM's PIM Research Laboratory and pilot plant offers expertise in feedstock development and optimisation

The PIM Research Laboratory and pilot plant at the Universidad de Castilla-La Mancha (UCLM) in Ciudad Real, Spain, specialises in the development and optimisation of feedstocks for the PIM industry. *PIM International*'s Nick Williams reports on a visit to the facility as part of a practical laboratory day ahead of the European Powder Metallurgy Association's recent Metal Injection Moulding short course in Barcelona.

In advance of the European Powder Metallurgy Association's (EPMA) Metal Injection Moulding Short Course in Barcelona, April 16-17 2015, a small number of participants took the opportunity to visit the recently established UCLM PIM Research Laboratory in the INEI (Instituto de Investigaciones Energéticas y Aplicaciones Industriales) at the Universidad de Castilla-La Mancha, located in the city of Ciudad Real, one hour by train south of Madrid.

The driving force behind UCLM's PIM laboratory is Dr Gemma Herranz Sanchez-Cosgalla, Tenured Associate Professor in UCLM's School of Industrial Engineering. A well-known figure in the European PIM industry, Herranz has overseen the creation of a laboratory with a wealth of facilities that is designed not only to enable PIM research, but also to serve as a partner to industrial producers who need support in the ongoing development of their commercial PIM operations. The laboratory has the facilities to offer support in all stages of PIM processing, with expertise to not only work in the development and enhancement of binder systems and feedstock, but also injection moulding, debinding and sintering processes, along with critical issues in MIM such as carbon control.

During the laboratory visit participants were taken through the basics of PIM binder systems and took the opportunity to question the UCLM team as they prepared, mixed, extruded and injection moulded a CIM feedstock.

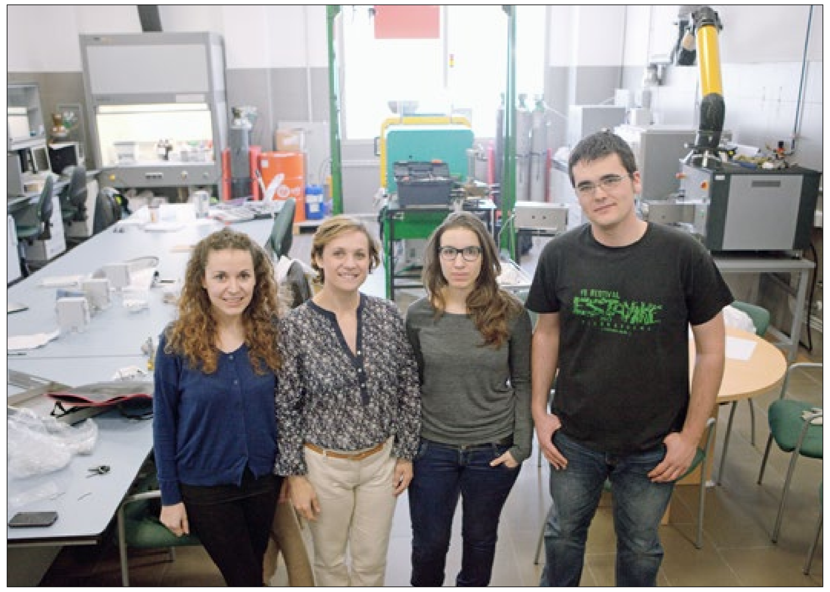

Fig. 1 Ana Romero, Dr Gemma Herranz, Bárbara Bellón and Santiago Cano in the UCLM PIM laboratory

Fig. 2 Dr Christian Kukla, Montanuniversität Leoben, Austria, speaks to students at the UCLM PIM laboratory

Fig. 3 Visitors from Austria, Italy and France speak with staff at the PIM laboratory

The role of UCLM's PIM Laboratory

Herranz explained that feedstock development and analysis was a core area of expertise at the laboratory. Whilst many firms have relied on commercially available feedstock, there may be any number of reasons why the need for a custom feedstock can arise, perhaps as a result of the unavailability of a key material, challenges in relation to moulding, or simply a desire to reduce a dependency on external suppliers.

For firms that blend their own feedstocks in-house, challenges may still exist in terms of process stability, processability and high part rejection rates. Herranz stated that whilst a company may have used a feedstock formula for many years, when problems arise they may not necessarily have the expertise to understand the causes at the most basic level, for example as a result of the use of two unsuited binder ingredients interacting, or polymer degredation as a result of inappropriate feedstock production parameters or injection moulding conditions.

Whilst much of the laboratory's long-term contract work for industrial partners is confidential, the team is experienced at working with a wide variety of PIM materials, from low alloy and stainless steels to tool steels and cobalt-chromium alloys, as well as all major materials used in Ceramic Injection Moulding.

"Our PIM pilot plant has all the equipment to perform the complete processing of PIM parts. Our focus is on the design of innovative feedstocks, their rheological characterisation and a detailed monitoring of each step of the production process," stated Herranz.

"Our service focuses on developing technology that can be transferred to our industrial clients for commercial production. In addition to creating and testing the appropriate feedstock, we are able to perform complete microstructural and mechanical characterisation tests in order to predict the final properties of real parts in service."

An international background in PIM research

Herranz has many years of experience in MIM research. She studied for her PhD in MIM technology at Carlos III University in Madrid after receiving a grant to work on a regional project relating to the MIM of advanced materials under the supervision of Prof José Manuel Torralba. Herranz stated, "In this project MIM was studied from four different approaches by four research groups - a polymer group, a physics group, a mathematics group and a PM group - and our role was as coordinator. This four-year project gave me the opportunity to study this technology from different angles." Herranz's PhD was the first in Spain to focus on MIM.

During this period Herranz travelled widely, studying under many leading researchers in the MIM field. After a period in the Chemistry Faculty of San Sebastian University, in the north of Spain, working on rheological studies under the supervision of Dr Antxon Santamaría she travelled to the CISP Center at Penn State University, USA, where she worked under the supervision of Dr Don Heaney and Prof Randall German. "During this period I worked on all the steps of the PIM process, but with a focus on feedstock mixing, rheology and injection moulding. I appreciated the opportunity to have interesting scientific discussions with others researchers and I am still in contact with many colleagues from those years, including Dr Sundar Atre, Dr Seong Jin Park, Dr Ivi Smid and Dr Rudolf Zauner."

After a period at the Austrian Research Center (ARC) in Seibersdorf, in which she worked in debinding and sintering optimisation under the supervision of Zauner, Herranz presented her PhD in 2004. "It was at this point that I moved to the University of Castilla La Mancha and created my own research group. I then worked in PIM uninterruptedly with the financial support of small regional projects. It was in 2010 that a European Fund for Regional Development (FEDER) project allowed us to set up the UCLM PIM Research Group. This FEDER project was supported by seven research groups at UCLM, along with the INEI research institute, ten Spanish companies and a number of European companies, research centres and associations. "

Commenting on the motivation behind the setting up of the UCLM PIM laboratory, Herranz told *PIM International*, "I believe that specialisation is the way to really make scientific and technological contributions. After my formative experiences in the PIM field I consider that we are able to make important contributions to this technology, from the basic fundamentals of feedstock formulation to the evaluation of new materials through the entire process chain. The biggest challenge as I see it is to ensure financial support for our operations and to be able to retain the specialists who are working in the laboratory over the long term."

Fig. 4 A UCLM researcher demonstrates CIM feedstock production to laboratory visitors

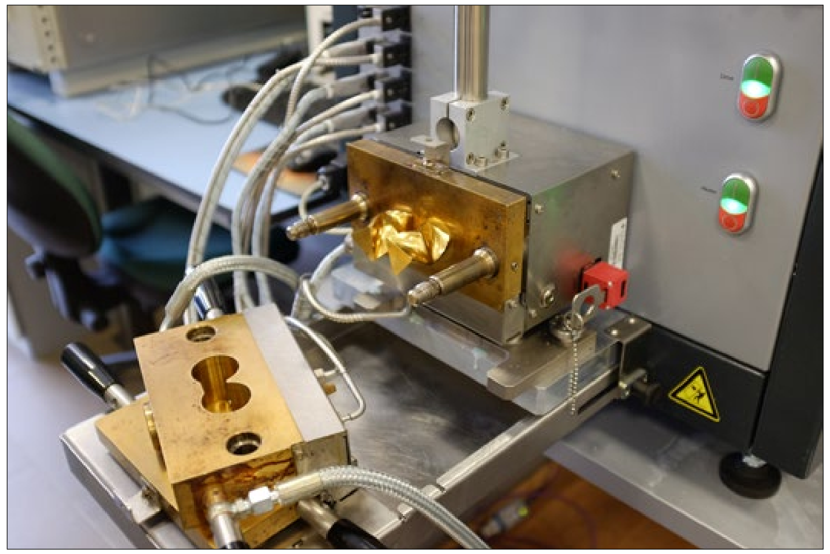

Fig. 5 The ThermoHaake double rotor mixer in the UCLM PIM laboratory

Partnerships with industry

The mission of the UCLM PIM laboratory is to provide consulting services to industry, as well as training people who wish to enter this industry. A specialist focus is, however, on the development of new or customised feedstock formulations and the optimisation of the entire process for each formulation.

Herranz stated, "Our mission is to be a centre of excellence for PIM consulting, training and testing. We are in a strong position to help meet the new challenges that face this technology. Our expertise is in the study of the influence of the composition, size and shape of the starting metal powder and the addition and influence of different binder compounds on final properties, as well as the influence of processing methods. We also focus on the processing of new or less well understood materials that can help open new applications for PIM technology. These materials can range from magnetic materials to superduplex steels and advanced ceramics."

Research facilities

The PIM laboratory has an extensive range of equipment for all aspects of the PIM process. A ThermoHaake double rotor mixer and twin screw extruder are used for the preparation of feedstocks, which are then

Fig. 6 Viscosity studies are demonstrated on a Dynisco LCR capillary rheometer at the UCLM PIM laboratory

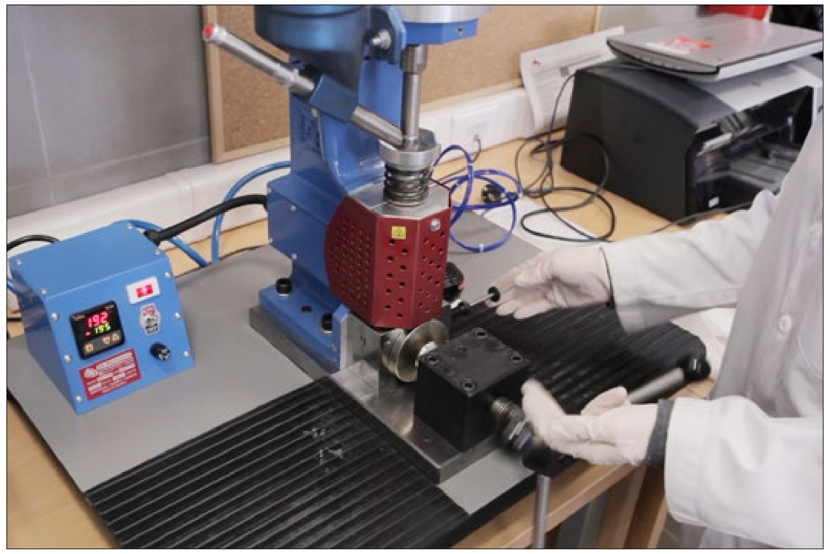

Fig. 7 Low pressure powder injection moulding on equipment from A B Machinery

granulated in a Retsch grinding mill. Viscosity studies are undertaken on a Dynisco LCR capillary rheometer. Injection moulding studies are performed on an Arburg Allrounder 270 S injection moulding machine with various injection moulds of differing standard geometries available. A low pressure injection moulding system is also used.

Various laboratory scale debinding and sintering furnaces, capable of operating at up to 1800°C, are available including systems that operate in controlled atmospheres and high and low vacuum. Carbon analysis is performed on a Leco CS230 elemental carbon analyser and density measurements are taken using a micrometric helium pycnometer and an archimedes balance. Thermal analysis is performed on a NETZSCH STA 449 C calorimeter. Mechanical testing facilities include Rockwell and Brinell durometers, Vickers and Knoop microhardness testing and a Shimadzu tensile testing machine. A metallographic sample preparation laboratory is also available, equipped with SEM and optical microscopes and an X-ray diffraction facility.

PIM in Spain

Spain may not immediately be considered a major player in the global PIM industry, however the country has a wealth of knowledge and experience. Ecrimesa SA, based in Santander, is one of Europe's largest MIM producers and supplies high volumes of components internationally to sectors including automotive and firearms. The company was also the first to purchase one of Cremer Thermoprozessanlagen GmbH's MIM Master continuous furnaces in 1992. The country also has a strong track record in PIM research, thanks in large part to the work of Prof José Manuel Torralba.

The UCLM PIM laboratory works closely with leading Spanish companies, however Herranz commented, "As PIM technology is not so well known in Spain – at least outside of the PM community - there are limitations to the number of collaborations that we can have in the domestic market. Some companies in our region have an interest in producing some parts by this technology instead of buying parts on the international market, but the initial investment is a too big a step for most of the companies. These companies are working mainly in casting and polymers for the automotive sector, or they are part of the medical device and dental industries, producing prostheses or orthodontics. Recently some companies have appeared to look at other aspects of the PIM chain such as feedstock production. Certainly there is a company with wide experience in ceramics that is developing specialised feedstocks for CIM."

The laboratory's consultancy projects typically have a minimum of six months duration, allowing time to go in-depth into a specific problem. "Our capacity to give quick answers to industrial problems is limited. Our focus is on providing close collaborative assistance to companies that would like to enter in the sector, or make long term enhancements to their processes to improve productivity and quality."

Academic research

The PIM laboratory has recently received a grant for a national project on TWIP (Twinning Induced Plasticity) steels in collaboration with Dr Jose María Cabrera at the Universidad Politécnica de Cataluña. Other cooperative research projects include work with the Universidad de Valladolid on corrosion and wear characterisation, the Instituto de Cerámica y Vidrio in Madrid for advanced ceramics developments, Montanuniversitaet Leoben in Austria for rheological analysis, and the University of Silesia, Katowice, Poland, for sintering analysis.

Fig. 8 Thermal debinding of metal injection moulded parts

Education and training

Given the widely recognised shortage of trained engineers in the PIM industry, centres such as the UCLM's PIM laboratory provide an invaluable service to industry by training and educating the next generation of young engineers. There are currently seven students working in the laboratory, six of whom are in the process of completing their degrees in Mechanical Engineering. A further student is studying for a Master's degree in Industrial Engineering and will be undertaking work for his final thesis in the laboratory.

Two PhD students, Ana Romero and Bárbara Bellón, are involved in all the activities of the laboratory as well as progressing their own research. Romero is currently an Assistant Professor at UCLM with five years of experience in PM and was a key figure in the setting up of the laboratory.

Herranz stated, "Our research group has a lot to offer industry in this respect. It has to be remembered that our students have to face real challenges when they do experimental work. They also need to find the most scientific justification for the results that they obtain and, for this purpose, technical and scientific published data has to be researched and referenced. All this work gives them the background knowledge, technical skills and abilities required by the PIM industry."

Fig. 9 Solvent debinding in the UCLM PIM laboratory

Outlook

The PIM industry continues to evolve at a rapid pace, with new applications and materials pushing the boundaries of the technology. New applications in the aerospace and automotive sector are demanding the highest levels of performance and process stability. In this context a centre of expertise in PIM feedstock development and optimisation can be seen to have a bright future. Herranz concluded, "Today we have close collaborations with other research centres and research groups around Spain and throughout Europe to complement our knowledge and work together on new challenges. New international collaborations are very welcome, from both companies and other research institutions."

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Growing demand from the aerospace sector drives MIM superalloys research

The aerospace sector is today one of the fastest growing areas for MIM technology, with superalloys being a key material for this high value market. Whilst aerospace manufacturers compete to be the first to announce new applications for Additive Manufacturing, they are generally far more discrete about publicising the major advances that are currently taking place in MIM aerospace applications. In this article Bernard Williams reviews three recent technical papers that give an insight into the technologies and materials being employed in this sector and spotlights a research chair which has been dedicated to developing complex shape MIM aero engine parts.

Metal Injection Moulding offers low-cost production route to high pressure compressor vanes for aero engines

The IHI Group in Japan has played an active role in the aviation industry since the mid-1950s, building a reputation for manufacturing environmentally friendly and fuel-efficient aero engines. The company is a major supplier of aero engines to the Japanese military and is also a major supplier to General Electric's GE-90 engine used on Boeing's 777 passenger jets, as well as the more recent GEnX engine used on Boeing's Dreamliner.

The IHI Group's Aero-Engine & Space Operation has been investigating the use of Metal Injection Moulding as a production process for the complex shaped assembled high pressure compressor vanes made from Alloy 718 superalloy powders with the objective of reducing cost and improving properties compared with wrought and machined Alloy 718 material. Fig. 1 shows the location of the high pressure compressor vanes in the cross sectional view of a gas turbine aero engine and Fig. 2 an external view of the compressor vane itself.

Shuji Ikeda and his colleagues in the Engine Technology Department, Research & Engineering Division, recently reported on their efforts to introduce MIM technology for the compressor vanes and their results

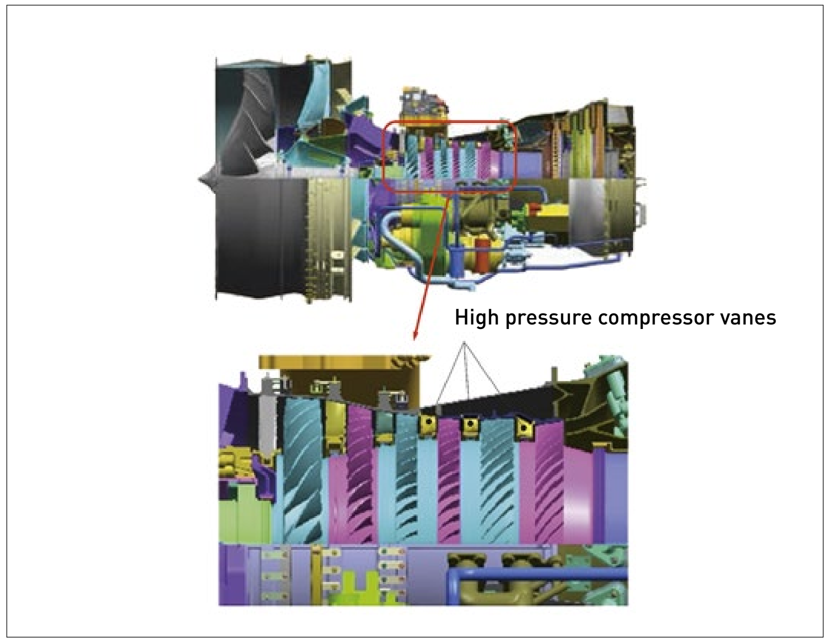

Fig. 1 Cross sectional view of a gas turbine aero engine showing the location of the high pressure compressor vanes [1]

Production method	Chemical compositions					
	Mo	Al	Ti	NbTa	C	O
	wt%					ppm
Gas atomisation	3.12	0.66	0.98	5.14	0.05	300
Water atomisation	3.02	0.27	0.73	5.01	0.05	4 900

Table 1 Composition of Alloy 718 metal powder [1]

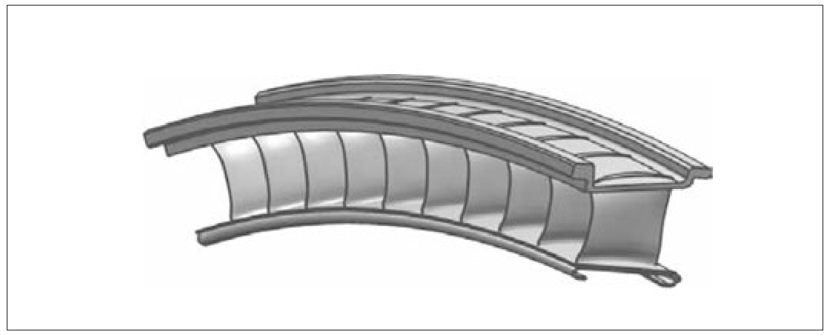

Fig. 2 External view of high pressure compressor vane [1]

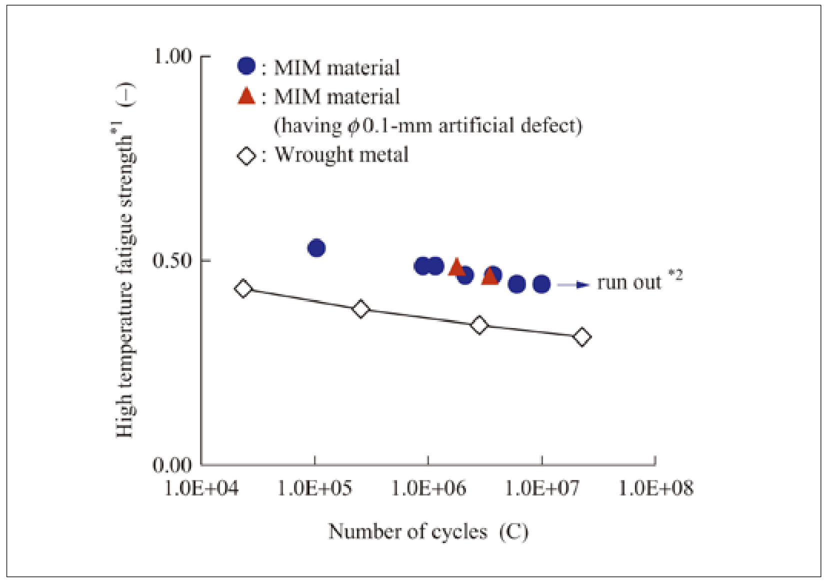

Fig. 3 S-N curve of MIM Alloy 718 [1]

were published in *IHI Engineering Review* (2014) [1]. Ikeda stated that in order to apply MIM to aero engine parts a certain level of dimensional accuracy has to be achieved in the production of MIM parts which can weigh in the region of 100 to 200 g, significantly heavier than the average MIM part weighing around 10 g. The researchers found that larger size MIM parts can have increased deformation during debinding and sintering and that suppressing this deformation is critical to the success of the MIM process.

In the MIM process studied at IHI Group, a fine Alloy 718 superalloy powder (see Table 1 for composition) having less than 20 µm average particle size was mixed with a binder made from multiple thermoplastic resins and wax. Both gas and water atomised powders were used with the objective of comparing the influence of increased oxygen content on the fatigue strength of the MIM test bars made from the water atomised grade. The binder was removed from the injection moulded parts by solvent debinding. A 0.1 mm diameter micropore defect was deliberately added to study the influence of microporosity in MIM parts.

The results on MIM test bars found that MIM Alloy 718 superalloy had tensile strength equivalent to that of wrought metal of the same composition and that MIM parts made from gas atomised powders had higher fatigue strength than wrought Alloy 718 superalloys even with the artificial defect as can be seen in Fig. 3. The reason for the higher fatigue strength in MIM Alloy 718 is attributed to the finer average grain size of 30 µm in the sintered test parts compared with 90 µm average grain size in the wrought grade.

In test production of MIM compressor vane prototypes using a conventional binder, it was found that dimensional accuracy after debinding and sintering was inadequate (Fig. 4). However, production of MIM prototypes using a unique specially developed binder, the composition of which was not disclosed in the report, was able to suppress deformation and achieve satisfactory dimensional accuracy as can be seen in Fig. 5 and has led to promising results for MIM technology in this important new field of application.

Binders studied for low pressure powder injection moulding Inconel 718 superalloys

Low pressure Powder Injection Moulding (LP-PIM) can be used to cost effectively mass produce small net shape metallic parts using moulding pressure generally lower than 1 MPa. LP-PIM involves mixing a low-viscosity binder formulation with metal powder having adequate morphology to fill the mould cavity. Binders for LP-PIM feedstock are generally made up from waxes, surfactants and thickening agents. Paraffin wax (PW), microcrystalline wax (MW) and natural wax such as beeswax (BW) and carnauba wax (CW)] are already widely used as the main constituents of PIM feedstocks. The surfactant agent acts as a bridge between the metallic powder and the other constituents to enhance the homogeneity of the feedstock as well as the mixing properties and a thickening agent is generally used to increase the viscosity of the mixture in order to prevent powder-binder separation. Stearic acid (SA), ethylene vinyl acetate (EVA), and low density polyethylene are also extensively used as the secondary constituents in LP-PIM feedstocks.

A team of researchers comprising Professor Vincent Demers (Department of Mechanical Engineering, Ecole de technologie superieure, Montreal, Canada), Professor Sylvain Turenne (Ecole Polytechnique Montreal), and Dr Orlando Scalzo (Pratt and Whitney, Longueuil, Canada), have been investigating the mouldability by LP-PIM of Inconel 718 powders using a variety of feedstock formulations, and the results were recently published in the *Journal of Materials Science* Vol. 50, (2015), 2893-2902 [2]. Inconel 718 is a high strength, age hardenable and corrosion resistant nickel-base superalloy extensively used in aero engines and components produced by PM and MIM to high final density have shown improved mechanical properties compared with conventionally produced Inconel 718.

The researchers state that the primary aim of the work was to investigate the impact of low viscosity binder systems on the low pressure Powder Injection Moulding of Inconel 718 feedstock. Viscosity of the powder-binder mixtures they state to be an important rheological property for mouldability with the main variables influencing viscosity being shear rate, temperature, solid loading, powder particle shape and size and binder composition. They used a gas atomised superalloy powder having spherical shape and average particle size of 12 µm with 60% powder loading in all the feedstock formulations (Table 2).

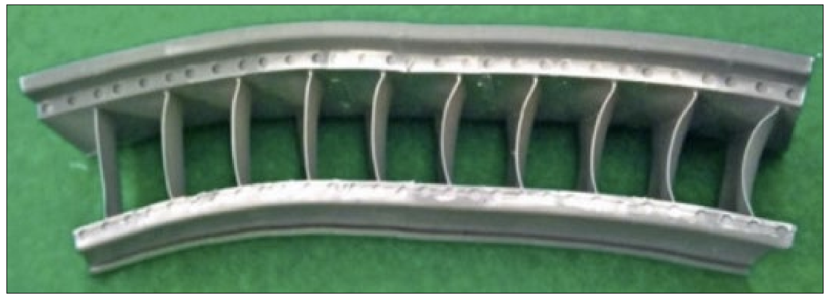

Fig. 4 Sintered MIM prototype vanes showing dimensional inaccuracy using conventional binder [1]

Fig. 5 Sintered MIM prototype vanes using newly developed binder [1]

Results are presented in the paper of viscosity measurements of all the paraffin wax (PW), microcrystalline wax (MW), natural wax-based (BW), stearic acid (SA), and ethyl vinyl acetate (EVA) feedstocks. It was found that during mixing the two best feedstocks are 40PW2 and 40PW3 due to their very high values of viscosity at low shear rate. During injection the best feedstock was found to be powder-binder mixtures containing PW and SA due to their very low values of viscosity at moderate-high shear rates. However, the low value of viscosity of these mixtures at low shear rate may induce a non-negligible powder-binder separation after injection or during the previous mixing stage and this will be the subject of future work. Another factor considered was injection moulding temperature and the best feedstocks were found to be 39PW-1SA (and other mixtures with SA) because of their low melting point between 50-54°C.

The authors of the paper conclude that, from a rheological perspective, there is no significant advantage to using microcrystalline wax or CW as a main component of the

"Inconel 718 is a high strength, age hardenable and corrosion resistant nickel-base superalloy extensively used in aero engines and components produced by PM and MIM to high final density..."

Feedstock	vol%										Mixing temperature [°C]
	Metallic powder	Paraffin wax #1 [PW1]	Paraffin wax #2 [PW2]	Paraffin wax #3 [PW3]	Micro wax #1 [MW1]	Micro wax #2 [MW2]	Bees wax [BW]	Carnauba wax [BW]	Stearic acid [SA]	Ethylene vinyl acetate [EVA]	
40PW1	60	40	–	–	–	–	–	–	–	–	70
40PW2	60	–	40	–	–	–	–	–	–	–	70
40PW3	60	–	–	40	–	–	–	–	–	–	70
20PW1-20PW3	60	20	–	20	–	–	–	–	–	–	70
14PW1-13PW2-13PW3	60	14	13	13	–	–	–	–	–	–	70
40MW1	60	–	–	–	40	–	–	–	–	–	70
40MW2	60	–	–	–	–	40	–	–	–	–	70
20MW1-20MW2	60	–	–	–	20	20	–	–	–	–	70
14PW1-13MW1-13MW2	60	14	–	–	13	13	–	–	–	–	70
40BW	60	–	–	–	–	–	40	–	–	–	70
40CW	60	–	–	–	–	–	–	40	–	–	90
20CW-20BW	60	–	–	–	–	–	20	20	–	–	90
14PW1-13CW-13BW	60	–	14	–	–	–	13	13	–	–	90
39PW1-1SA	60	39	–	–	–	–	–	–	1	–	70
35PW1-5SA	60	35	–	–	–	–	–	–	5	–	70
30PW1-10SA	60	30	–	–	–	–	–	–	10	–	70
20PW1-20SA	60	20	–	–	–	–	–	–	20	–	70
39PW1-1EVA	60	39	–	–	–	–	–	–	–	1	90
35PW1-5EVA	60	35	–	–	–	–	–	–	–	5	90
30PW1-10EVA	60	30	–	–	–	–	–	–	–	10	90

Table 2 Volume fraction of Inconel 718 powder and polymers used for feedstock formulations for low pressure Powder Injection Moulding [2]

feedstock for low pressure Powder Injection Moulding of Inconel 718 powders. They stated that the best candidate feedstocks are the mixtures containing PW1 and SA while feedstocks based on PW1, BW or containing a small amount of EVA could also be considered as good. Therefore, these constituents can be used as the main waxes for the optimisation of more complex LP-PIM feedstock in future works. They also stated that, from a practical perspective, the viscosity measurements can be used to control the quality of feedstock in production as well as to measure the impact of binder in development of new feedstocks. In this sense, several proprietary LP-PIM binder formulations are presently used with an impressive degree of mould filling performance.

MIM 418 superalloy shows superior properties for high performance applications

K418 is one of the most common cast nickel-base superalloys offering high creep strength, good fatigue properties and superior oxidation resistance. However, the properties of cast K418 ingot material can be adversely affected by defects such as segregation of alloying elements, very coarse microstructure with grain size around 3-4 mm, shrinkage and undesirable phases (Laves). Additionally, its high hardness makes it difficult to machine to produce complex shaped parts such as turbochargers. To overcome these issues researchers at the National Engineering and Technology Research Centre for Nonferrous Metal Matrix Composites, Beijing, in cooperation with the Powder Metallurgy Research Institute at the Beijing University of Science and Technology, have been investigating the use of Metal Injection Moulding to produce complex, near-net shape components from K418 superalloy powder having the following composition: Cr12.33%-Al6.18%-Ti0.8%-Mo4.35%-Nb2.2%-Fe <1%-B0.02%-C0.12%-Zr0.09 – balance nickel. Fu-Bao Yang and colleagues recently published the results of their work in *Rare Metals* (January 2015) [3].

They stated that the K418 superalloy powder used was produced by gas atomisation with powder particles having average particle size of 23.09 µm and the median particle size of 17.44 µm. The volume fraction having particle size greater than 30 µm is around 16.5%. The powder particles were found to have a fine dendritic structure due to rapid cooling, and some carbides are precipitated in the grain boundaries.

The MIM grade K418 powder was blended with a multi-component binder system and the feedstock was injection moulded to produce tensile test bars. Debinding was done using a two-step solvent/thermal operation and the test bars were sintered at 1240°C under high vacuum for 2 hrs to 97% theoretical density. The sintered microstructure has a fine equiaxial grain size of 20-30 µm with pores in the structure being less than 10 µm. Even in the as-sintered condition the mechanical properties of the MIM 418 test pieces were superior to the cast and solution treated K418.

To eliminate the remaining porosity in the sintered MIM material and to enhance mechanical properties even further, the researchers applied Hot Isostatic Pressing (HIP) treatment at 1200°C for 2 hr. This resulted in a theoretical density of 99.5% with the remaining small pores after sintering being almost totally eliminated. Also the grain size and shape did not change significantly after HIPing contrary to expectations that grain size increases when holding at high temperature. This is attributed to the pores in the grain boundaries and carbide which can hinder the

Research Chair focuses on the use of Powder Injection Moulding for complex shaped aero engine parts

An Industrial Research Chair established in 2012 in the Department of Civil and Resource Engineering at Dalhousie University, Halifax, Nova Scotia, Canada, is focusing on developing strategies to reduce greenhouse gas (GHG) emissions to mitigate global warming. Major contributors to GHG emissions include energy consumption in the manufacture of industrial components and fuel consumption in the transportation sector. The Industrial Research Chair programme will address GHG emissions in the aerospace industry through the development of near net shape (NNS) manufacturing techniques applied to nickel-based superalloy engine components.

Dr Stephen Corbin, who is leading this research programme in conjunction with his collaborators at Pratt and Whitney Canada (P&WC), will aim to develop and improve methods used to produce complex shaped aero engine components. Dr Corbin states that aero engine components will be created by brazing together several simpler parts, made through PIM and sintering, thus producing a more complex shape. Compared to traditional non net-shape cast or wrought routes, this approach to manufacturing will, stated Dr Corbin, reduce the need for costly material removal steps (i.e., machining), resulting in lower energy usage and reduced material waste. This approach will also lead to new designs which are not possible with conventional manufacturing routes.

A primary activity of the programme, which Dr Corbin said is still ramping up, will involve the combined use of high temperature thermal analysis tools capable of measuring weight, enthalpy, dimensional and thermal diffusivity changes in superalloy materials under conditions which simulate industrial scale brazing and sintering. Throughout his career Dr Corbin has used these techniques to understand complex metallurgical reactions taking place during the sintering of Powder Metallurgy mixtures and soldering and brazing. The insight gained from this work has led to the development of new joining and sintering processes and the optimisation of industrial manufacturing methods. His most recent focus has been on the development of sustainable manufacturing practices which take advantage of the NNS attributes of both PM and brazing in the aerospace industry, with potential extension to other materials intensive manufacturing sectors.

The optimised brazing and sintering techniques will be used in P&WC operations to reduce engine production costs, while developing more sustainable manufacturing practices, resulting in a reduction in GHG emissions. In addition to having a positive impact on the environment, the work undertaken under this Chair will enhance P&WC competitiveness in the global aerospace industry and promote Canadian economic growth and job creation. The Programme Chair will publish its findings in forthcoming technical report.

Dr Stephen Corbin, Programme Chair for the 'NSERC/Pratt and Whitney Canada Industrial Research Chair in Structural Brazing and Processing of Powder Metallurgy Superalloys' at the Department of Civil and Resource Engineering, Dalhousie University

State of alloy 418	Tensile strength MPa	Yield strength MPa	Elongation %
Sintered	1,085	746	11.4
HIP treated	1,271	756	16.8
As-cast	921	800	4.6
Solution treated	945	792	6.0

Table 3 Mechanical properties of sintered, HIP-treated, as-cast, and solution-treated samples

migration of grain boundaries.

The researchers found that mechanical properties of sintered and HIP treated MIM 418 test pieces were significantly better than as cast and solution treated K418 superalloy. As can be seen in Table 3, as-sintered tensile strength of 1085 MPa increases to 1271 MPa in the HIP treated condition whilst yield strength rose only slightly to 756 MPa and is a little lower than the cast material.

The increased strength in the MIM418 superalloy can be explained by the finer grain and carbide dispersed in the alloy. Elongation values for sintered and HIP treated MIM418 were 11.4% and 16.8% respectively – a significant improvement on cast K418 elongation values. Hardness value for the MIM418 alloy material after HIP treatment is HV0.5 400 compared with HV0.5 300 for the cast K418 alloy.

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[1] Development of Metal Injection Molding Process for Aircraft Engine Part Production, S Ikeda, S Satoh, N Tsuno, T Yoshinouchi, M Satake. *IHI Engineering Review*, Vol.47, 2014, 44-48).

[2] Impact of binders on viscosity of low-pressure powder injection molded Inconel 718 superalloy, V Demers, S Turenne, O Scalzo. *Journal of Materials Science* (2015), 50: 2893-2902.

[3] Microstructure and mechanical property of MIM 418 superalloy, Fu-Bao Yang, Y-H Jing, D Li, L Zhang, D-Q Li, and Q Zhu, published in *Rare Metals*, January 2015

Download our free report on the processing and properties of Metal Injection Moulded Superalloys

The production of MIM superalloys is one of the few remaining secretive areas of Metal Injection Moulding technology, with information on applications in the aerospace sector, and the necessary properties achieved, kept confidential in order to protect decades of privately funded research and a competitive advantage. There remains, however, a significant volume of data available on what can, and is, being achieved via MIM processing.

In the March 2013 issue of *PIM International* Burghardt Klöden, Thomas Weissgärber and Bernd Kieback (Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Dresden, Germany) and Ingolf Langer (Schunk Sintermetalltechnik GmbH, Germany)presented a detailed analysis of published work to-date and considered the potential for this area of MIM technology.

This 14 page 5,600 word review, featuring 14 tables, 11 figures and 47 references to published literature, is available to download free of charge from the *PIM International* magazine archive. The review focuses on:

- Superalloys by MIM
- The first generation of MIM superalloys: Udimet 700, Inconel 718, Inconel 625, Inconel HX
- Second generation of MIM superalloys: Inconel 713, Nimonic 90, Other alloys
- Applications for MIM superalloys in industry
- A review of published processing and properties data and challenges ahead
- Summary and outlook
- References

To download your free copy of this issue visit www.pim-international.com and navigate to the Magazine Archive and the download page for *PIM International*, March 2013, Vol 7 No 1.

Above: A single MIM compressor vane (top) and MIM vane cluster prototype (bottom) produced by assembling and sinter-brazing multiple MIM components, as featured in our free report. Originally published in the paper by S. Sikorski, M. Kraus, C. Müller, Cost Effective Manufacture via Net-Shape Processing (Proceedings RTO-MP-AVT-139) (2006), p. 9-1 and featured in PIM International's review of MIM superalloys.

Energy management in the Metal Injection Moulding industry

In a keynote presentation and workshop at the MPIF's MIM 2015 International Conference on the Metal Injection Molding of Metals, Ceramics and Carbides, February 23-25, Tampa, Florida, USA, Dr Robin Kent, Managing Director of UK-based consulting engineers Tangram Technology, addressed the topic of energy management in MIM. In this article Dr Kent reviews the methodology and underlying philosophy for energy management and control and provides important insights and tips of particular relevance to the MIM sector.

Unstable energy costs and decreasing security of energy supplies are global concerns and materials processors around the world are suffering from decreasing margins as energy cost increases cannot be passed on to customers. Negotiations with power suppliers on prices often have little effect. Despite the adverse effects on energy costs and supply, few companies have carried out even the most basic actions to reduce their energy consumption. Yet, this is one of the easiest actions that they can take to reduce costs and improve competitiveness.

Metal Injection Moulding (MIM) is relatively energy efficient compared to other metal processing methods, but is still energy intensive and processors are only now beginning to realise that energy is a significant cost that is both variable and controllable. Despite this recognition, reliable information on the energy demand of the process is very difficult to obtain and few MIM processors have even begun the process of understanding their energy use.

The MIM industry generally regards energy as a fixed and uncontrollable overhead cost, but this is untrue. Energy is a variable and controllable cost and most processors could reduce energy use by up to 30% through simple management, maintenance and investment actions.

Fortunately for most MIM processors, the margins are still sufficiently high that energy is a comparatively minor cost, but this does not mean that it can be ignored.

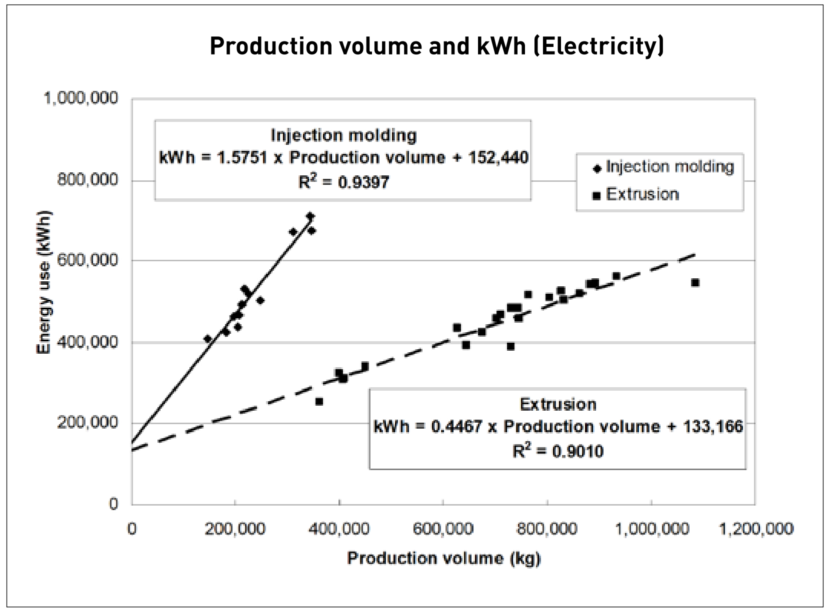

Fig. 1 PCL for injection moulding and extrusion sites (monthly data)

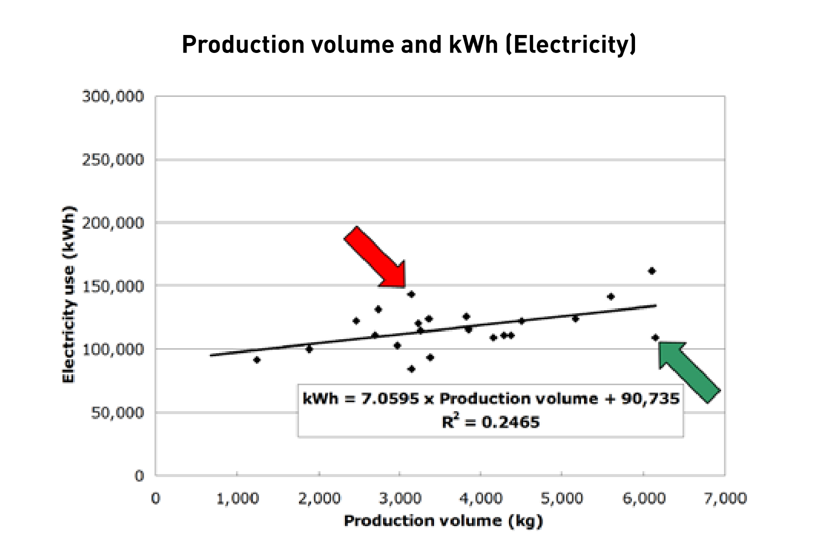

Fig. 2 PCL for MIM Site 1 (monthly data)

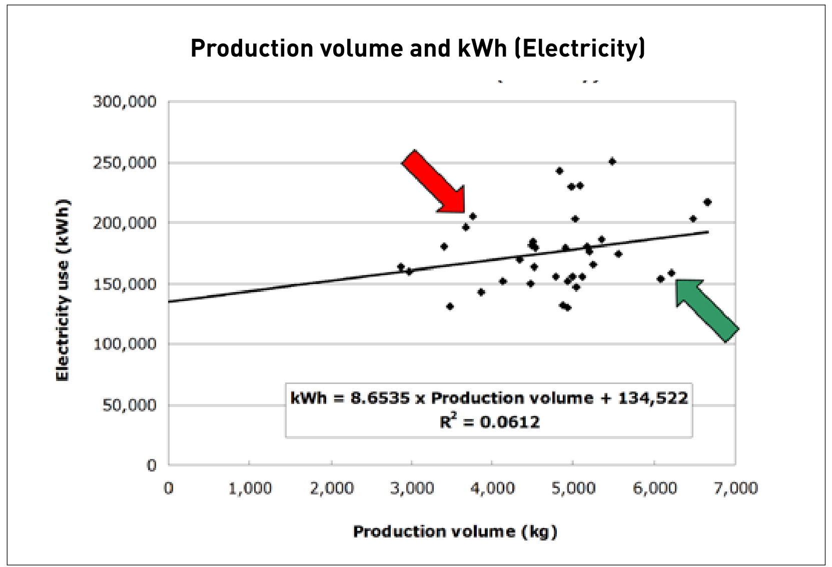

Fig. 3 PCL for MIM Site 2 (monthly data)

Whether the motivation is financial or environmental, there is a need to manage energy just like any other variable cost.

Energy as a variable cost

Energy use in any manufacturing process is a combination of two components: base load and process load.

The base load is the fixed element of energy use. It is incurred irrespective of whether production is taking place and does not change as output changes. This is the load used for heating, lighting, compressed air leaks and pumps operating when there is no production at all. It also includes losses from operating motors and other equipment with operating losses.

The process load is the variable element of energy use and, for most processes, it varies directly with the production volume. This is the load used to actually run process machinery.

The base and process loads can be readily defined by using available information. The energy used (in kWh) and the related production volume (in kg) for at least twelve weekly or monthly periods should be recorded. These data should then be plotted using a scatter chart and the equation of the best-fit line for the data found. The linear line of best-fit is the Performance Characteristic Line (PCL) and a typical result for most processes will be as shown in Fig. 1.

The equation of the best-fit line can be used to separate the base and process loads and assess the consistency of the site operations:

- The base load (in kWh) is the intersection of the best-fit line with the vertical axis. For the injection moulding site described in Fig. 1, the base load is 152,440 kWh/month and, for the extrusion site, the base load is 133,166 kWh/month. These values are almost 30% of the total site energy use and are primarily due to operating machinery or services with no productive output. Reducing the base load is generally possible without affecting operations in any way and to do so can be extremely profitable.
- The process load (in kWh/kg) is the slope of the best-fit line. This is the average energy used to process each kilogram of material and shows the processing efficiency of the site. The injection moulding site has a process load of 1.5751 kWh/kg and the extrusion site has a process load of 0.4467 kWh/kg
- The consistency of the site operations can be assessed from the R^2 value. This is the correlation coefficient of the PCL, e.g. 0.9397 for the injection moulding site and 0.9010 for the extrusion site.

A good correlation coefficient ($R^2 > 0.7$) indicates good consistency of energy use. This is not the same as good energy management but it does indicate that the site is consistent. This makes improvement easier to manage.

A poor correlation coefficient (R^2 value < 0.7) indicates poor consistency of energy use. This is generally the same as poor energy management and indicates that the site is inconsistent. This makes improvement difficult to manage.

These PCLs show that energy use varies directly with production volume and can be used to assess a site's energy performance. If the actual production volume is simply fed into the equation for the PCL, the result is the predicted energy use for the given production volume. For the injection moulding site shown in Fig. 1, if the production volume is 200,000 kg, then the predicted energy use will be:

kWh = 1.5751 x 200,000 + 152,440 = 467,460 kWh

Monitoring and targeting

Production accountability for energy use is then possible by comparing the predicted and actual energy use for the actual production volume. This simple approach provides a vital tool in setting targets and assessing performance based on the historical performance. The PCL can also be used to forecast a site's future energy use based on the sales forecast. The sales forecast can be translated into production volumes and the PCL can then be used to predict the energy use and cost.

The PCL gives vital information on sites in order to define where reductions in energy use and cost can be sought. Sites can:

- Reduce the base load to reduce the fixed costs - this mainly involves switching something off and is a certain means of making savings because the energy used is not production related, e.g. idling machines with no production, compressors running with no production etc.
- Reduce the process load to reduce the variable costs - this involves improving production efficiency and is an objective that should always to be sought.

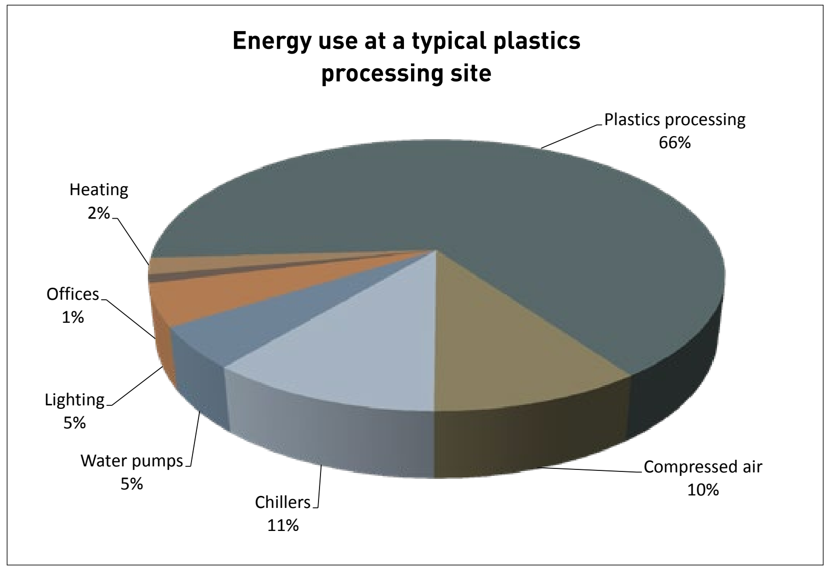

Fig. 4 Energy use at a typical plastics processing site

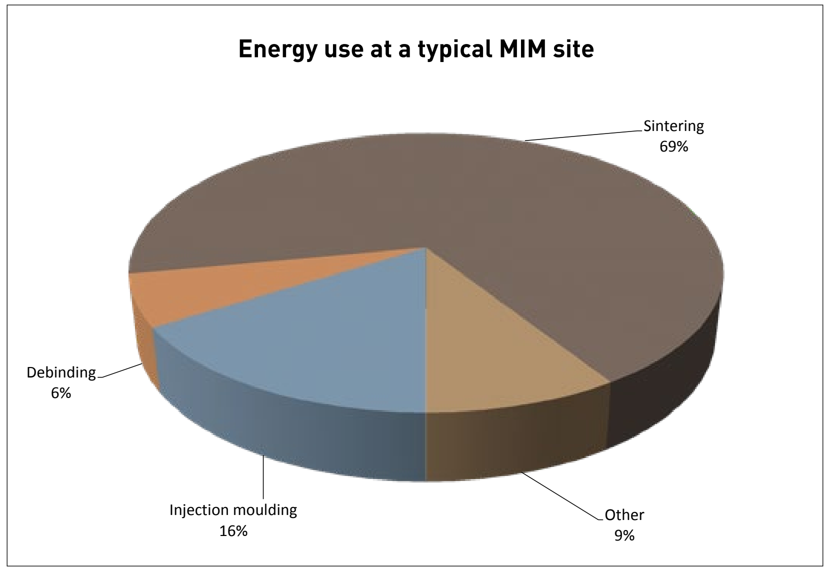

Fig. 5 Energy use at a typical MIM site

What about MIM?

Data from three MIM sites were provided for analysis and the data for two of these sites are shown in Figs. 2 and 3.

Both of these sites showed poor consistency of energy use ($R^2 < 0.7$) and both showed months where the production volume almost doubled but where energy use actually decreased. The energy uses at these sites must therefore be deemed to be not under control.

The base loads at both sites are > 75%. This is a very high figure for any site and indicates very high constant loads, e.g. continuous furnace operation with no production throughput, and a high fixed energy cost. In both cases, there is therefore an opportunity to reduce energy costs by simply reducing energy use that is unrelated to production. At an energy cost of $0.10/kWh (the total cost including the fixed element of the electricity bill), these sites have an energy overhead cost of $9,000 - $13,400 per month. High fixed costs are never an advantage.

The process load for these sites varies between 7.06 and 8.65 kWh/ kg.

At an energy cost of $0.10/kWh this means that these sites have a process energy cost of $0.71 - $0.87/kg processed.

The energy performance of the sites is similar, but it can be seen that Site 1 has a far better energy performance: it is more consistent, has a lower base load and has a lower process load. This site therefore has an operating cost advantage.

Where is energy used in MIM?

Understanding where a site is using energy is fundamental to managing use and reducing energy costs. Sites need to know where the money is being spent before trying to reduce the expenditure.

For plastics processing, site energy use is distributed approximately as shown in Fig. 4. For MIM, there are relatively few data available, but aggregated results from three MIM processors show energy use to be distributed as shown in Fig. 5.

This shows that, for a typical plastics processing site, the processing machines will use the most energy, whereas, for MIM sites, the sintering process is thought to be the major energy user. Despite this, most MIM sites have no real knowledge of where the energy that they pay for is being used. MIM sites need a much better understanding of where they are using energy and one of the best, and most accurate, tools is an energy map of the site.

An energy map is a model of the energy use at the site. This provides a visual and mathematical model of energy use that is validated using billing data or sub-metering (a sample energy map for injection molding is available free from www.tangram.co.uk/energy). The energy map allows efforts to be targeted so that they can have the most effect.

It is straightforward to set up an energy map, using simple monitoring equipment and operating hour data, and this should be one of the first tasks for any MIM company in trying to understand and minimise energy use. Energy mapping provides the essential information for setting priorities.

It should be noted that lighting is a very minor use area. So, the targeting of lighting when seeking to reduce energy use is not justified as being a priority action. There is a need to use energy mapping to identify the areas where significant levels energy and money can be saved.

Making savings

Summarising energy management in a short article such as this is an unenviable task and therefore the task has been restricted to the offering of some initial suggestions for reducing costs. There are many other ways to reduce costs; those given here are simply some that are easy to implement and that generally have quick returns.

"Energy management is the same as the management of any other resource; control needs to be applied to the procedure and measurement is fundamental."

Management

Energy management is the same as the management of any other resource; control needs to be applied to the procedure and measurement is fundamental. Measurement leads to management; but only if it is on the real management agenda. The following suggestions are offered in this context:-

- Make someone responsible and give them targets
- Report the results widely to emphasise that the issue is being taken seriously
- Involve the whole company by showing the results and rewarding performance
- Use the experience of the workforce and train the staff to develop their expertise through 'go-see' exercises
- Use the data from the PCL to set targets for performance
- Obtain the interval data from your supplier and analyse the bill
- Learn to read the electricity bill and look for hidden charges.

Maintenance

Maintenance is not simply the maintenance of the machinery. It is a whole range of activities that do not require significant investment and yet can have a remarkable effect on energy use and costs. Maintenance is about how the site is operated and in this context the following suggestions are offered:-

- Using large machines for small products always wastes energy. Check that all jobs are on the appropriate machine and that the machines and processes are fully utilised. The energy efficiency of any machine decreases as the operating conditions move away from the design conditions
- Optimised machine settings reduce energy use. Ensure that the machines are set correctly, record the settings and do not change them unless absolutely necessary
- Use Statistical Process Control to control machine settings and operations.

Machines use energy even when idling and this can be anything from 52% to 97.5% of the full energy consumption. An idling machine is not 'free'. Idle periods of greater than 45 minutes may mean that it is cheaper to switch off and restart or reduce temperatures to 'set-back' conditions. The minimum stand-by settings should be found and setting sheets established so that operators always leave machines in this condition when not producing. Relevant suggestions are:-

- Develop and use effective start-up, stand-by and close-down sheets to formalise machine settings and operations
- Stop supplying services, for example compressed air and cooling water, to idle machines and tooling, where this can be done safely
- Switch off heaters and ancillaries (fans and pumps) between runs, again where this can be done safely
- Monitor machine energy use to identify machine deterioration.

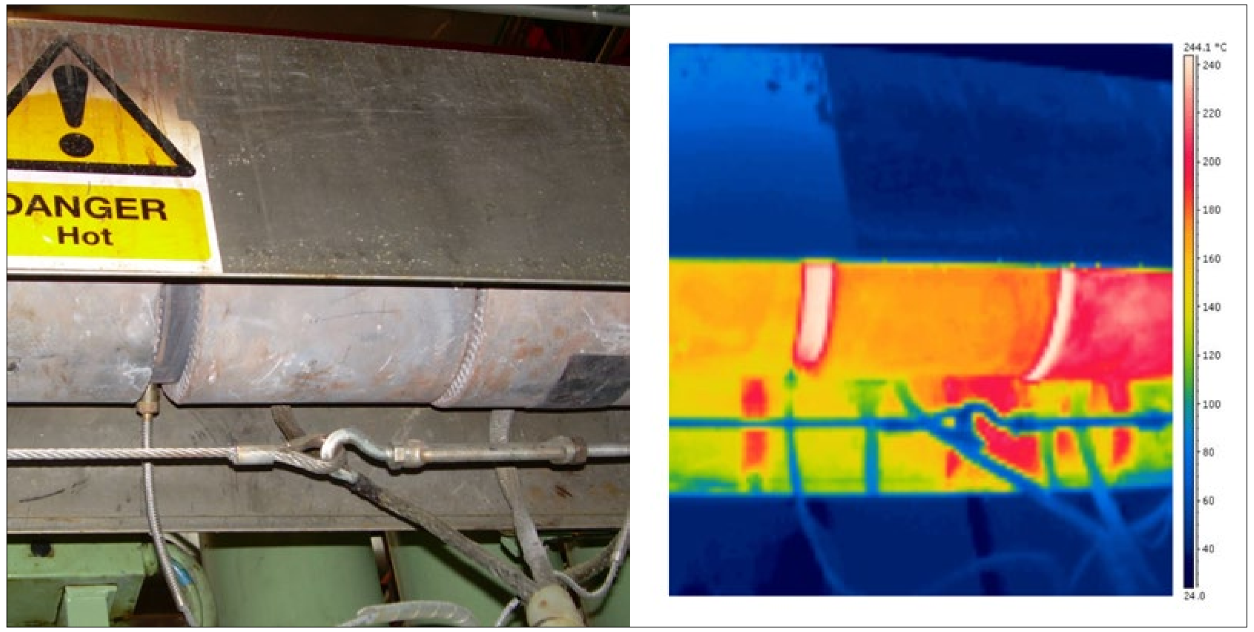

Fig. 6 Uninsulated barrels heat the atmosphere and raise process loads

Services

For many sites, the 'invisible' services, such as chillers, compressors, pumps and fans, will contribute up to 30% of the total energy use. These will generally be hidden away in services areas and, whilst they are not the largest energy user, the services areas may provide the easier savings.

For any service, the best approach is to "minimise the demand and then optimise the supply":-

- Up to 40% of the compressed air generated at sites is lost through leaks. The leaking noise that can be heard at most sites signifies that profits are leaking away
- A simple survey, with leaks tagged and repaired as soon as possible, can greatly reduce leakage. The only tools needed are a good sense of hearing, some soapy water and a brush
- Stop the use of compressed air for ventilation, cooling or conveying material or products - any other method is cheaper
- Check that compressed air is not being generated at a higher pressure than required
- Minimise the demand for cooling water by using insulation to prevent heat gains except where they are useful. If an item is cold to the touch, then it probably needs insulation
- Check that cooling water is at the maximum temperature and minimum quality
- Check that cooling water is efficiently treated and distributed
- Set downstream handling systems to operate 'on-demand' - link the controls to the machine operation.

Processing

Moulding

Electric moulding machines have a greatly reduced energy use compared with older hydraulic machines. On hydraulic machines, the system needs peak power for only a very limited time and is overrated and idling for most of the time. Suggestions are:-

- Always consider all-electric machines for new purchases
- Uninsulated barrels have poor thermal efficiency that can be improved by pre-seating the heating element to the barrel, by using flexible metal bearing compounds, by using insulated heater bands and most of all by using barrel insulation (Fig. 6).

Debinding and sintering

As with any heating process, the major challenge is to prevent heat loss from the process and to make sure that the input heat energy is concentrated on the product and not lost to the system. The following tips should be followed:-

- If the equipment is hot to touch, it probably needs insulation Insulate hot surfaces to prevent heat losses
- Reducing the thermal mass in the furnaces will reduce the heat needed for sintering
- Investigate alternative heating methods, for example IR heating
- Ensure that furnace seals and insulation are in good condition and are well maintained
- Investigate Variable Speed Drives (VSDs) for furnace fans (circulation and exhaust).

The real secret is not in the technical aspects, but is in the management attitude. A desire to reduce costs through good energy management and an effective implementation and monitoring programme will always produce results and financial benefits.

Investment

The cost of the energy used during the lifetime of almost any piece of capital equipment will be more than the initial purchase price and therefore the initial purchase price or payback on it should not dominate the decision-making process. Instead, there should be a focus on the 'whole life' cost of the investment and a consideration of the long term cash flow in order to identify the equipment with the least cost. Improved energy efficient technology now makes it possible to re-equip a factory for permanently lower operating costs.

Potential areas for investment include:

- Energy efficient motors and VSDs for pumps and fans
- Compressor controls and VSDs
- All-electric injection moulding machines
- Furnaces with improved insulation
- Lighting schemes and controls (although the savings here may be small, they are important psychologically for the staff).

These are all projects where the technology has improved rapidly and has proven energy saving benefits. Typical projects have paybacks from six months to more than four years. Investing in energy efficiency projects can significantly improve profits. The following suggestions should be considered:-

- Make an 'energy efficiency assessment' an essential part of the capital expenditure approval process. No assessment of operational energy use = No capital expenditure approval
- Obtain proof of the energy efficiency of equipment and check that it is applicable to your project and needs
- Be prepared to pay slightly more for energy efficient products, but be prepared to reap the benefits over the life of the equipment
- Look for projects where the rules can be changed and make energy saving automatic.

Concluding remarks

Energy management is a relatively straightforward and logic-based process and does not need to be driven by a desire to save the environment. It is good basic management of the process and good financial sense. Early attention to the issue will increase company profits and environmental benefits will follow.

Acknowledgments

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ExOne®: Binder Jetting technologies for Powder Injection Moulders

The Powder Injection Moulding industry has always been limited by its competitiveness in low volume and prototype part production, primarily because of high initial tooling costs. As many producers now look to Additive Manufacturing to fill this gap, one technology that may appeal to the PIM industry is Binder Jetting. As ExOne's Jared Helfrich, Jesse Blacker, Dr. Howard Kuhn and Michael Orange explain, this process allows PIM producers to, in many cases, use their existing debinding and sintering technologies to process parts manufactured on a range of Binder Jetting systems.

Powder Injection Moulding (PIM) is well established as a unique and economical process for the manufacture of medium to high volumes of small, complex precision components in competition with technologies such as machining, investment casting or die casting. More recently, 3D Printing or Additive Manufacturing (AM) technologies have developed out of an R&D based environment to address the need for greater complexity, localised manufacturing and reduced time to market. Today, both PIM and AM, each with their own unique benefits, provide viable process options for manufacturers.

These process options occupy distinct regions in the volume versus complexity space, as shown in Fig. 1. While PIM continues to grow, the addressable market for its industries and applications has some limitations. In particular, the cost of materials in powder form is considerably higher than in wrought form and the tooling and equipment required for each part limits the part size and complexity. In order to make the end applications economical for the tooling and capital resources required, large production runs into the thousands of identical parts are necessary. Additionally, educating customers on the design flexibility and excellent mechanical properties available through PIM technologies remains a challenge. Nevertheless, as these technologies proceed through their growth phases and customer applications expand, we will continue to see solid growth.

While AM technology is disruptive to subtractive processes such as machining, it should be considered complementary to the PIM processes. AM builds parts additively, layer by layer. As a result, tooling is not required, which helps reduce the

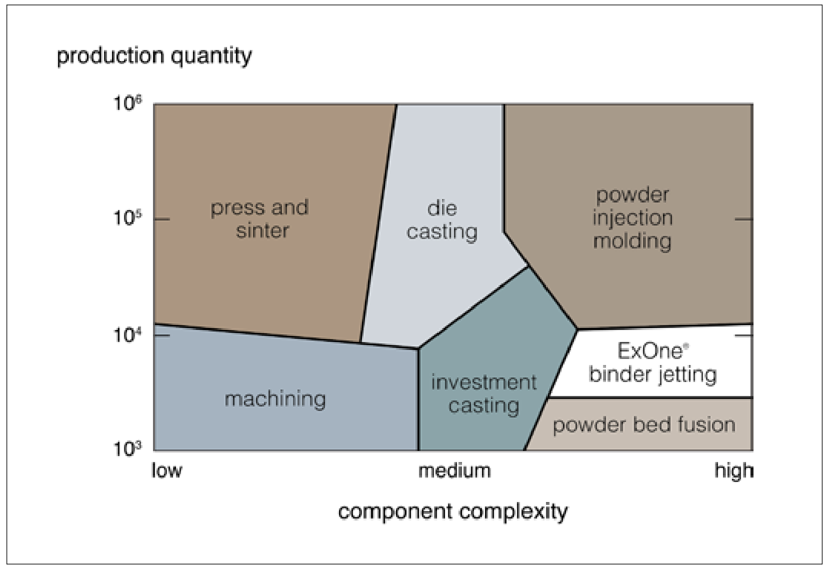

Fig. 1 Production technologies, volume vs. complexity (Modified form of chart from Injection Molding of Metals and Ceramics, Randall M. German and Animesh Bose, Metal Powder Industries Federation, 1997, 301)

Fig. 2 IN 625 alloy aerospace turbine blades

limits on part shape and complexity. In addition, prototypes and small run production lots now become economical. With the spectrum of AM processes ranging from material jetting to material extrusion and powder bed fusion, along with the material sets including polymers, ceramics, and metals, the range of applications and target markets for AM technologies is well diversified.

In general, AM has lowered the barriers for manufacturing and increased speed to market by enabling faster prototyping and short run production. This has been done by removing the tooling or patterns that restrict designs and lengthen lead times, eliminating expensive machining processes for complex parts, and enabling digital design ownership and flexibility.

Among the AM processes is Binder Jetting 3D printing, which grew out of a licensed process from Massachusetts Institute of Technology (MIT). Binder Jetting encompasses spreading a layer of powder material, typically 50-100 microns in thickness, followed by a printhead, similar to an inkjet printer, that selectively deposits a liquid adhesive, or binder, onto the powder bed based on a sliced 3D solid model file. Once the printhead has completed the layer, the build platform drops, a subsequent layer is spread and the process is repeated until a completed part is printed from the "bottom up."

Production synergies with PIM

The Binder Jetting 3D printing process produces a bonded green part that can either be partially sintered, sintered and infiltrated with another material, or highly sintered to a fully dense monolithic material. In other words, green parts produced by the Binder Jetting AM process are subjected to the same thermal processes as are the green parts produced by the PIM processes. This synergy not only leads to technical cross-pollination, but it enables expanded markets through more complex parts, larger parts and economical prototyping or short run production. Although additional post processing heat treatments are required for binder jetting, these can be conveniently integrated with most PIM manufacturing operations which already have this installed base of equipment such as debinding and sintering furnaces.

With the introduction and advancement of Binder Jetting 3D printing, the addressable markets for PM technologies can now be expanded. Not only are the standard AM process benefits realised, such as the elimination of tooling, reduction of scrap and cost of machining, speed to market with rapid prototyping and greater design freedom, but unique features of Binder Jetting provide additional opportunities. First, the volumetric output of Binder Jetting, as measured in cm^3/hr, allows the process to reach series production volumes for certain applications and markets. These production quantities can fulfil a unique niche in that the production volume may not be enough to justify PIM (generally regarded as requiring a production run of at least 5,000-15,000 units, depending on the application), but could be too large to justify alternative AM processes.

The various product forms and nature of Binder Jetting allow for broader materials selection and greater use in general industry including porous applications (metallic or ceramic filters), ceramic or metal matrix composites (cutting tools/wear parts/electrical contact pieces), or structural automotive and aerospace components.

Larger near net shaped parts with complex designs and expensive materials can also be printed, sintered and HIPed using the ExOne larger build envelopes. Presently, specialty Powder Metallurgy technologies using HIPing or canning methodologies can compete with machining processes on larger complex parts. With the elimination of tooling, these parts can now be printed in a green form state and follow similar heat treatments to achieve the desired densities for a given application. The opportunity for larger parts at the build rates listed above is a unique characteristic to Binder Jetting that not all AM processes can handle.

The future of Binder Jetting 3D printing as a complementary process to traditional PIM is largely uncharted territory. The adoption of Binder Jetting for future applications and markets rests with materials research in both metals and ceramics. Many of the applications will begin in traditional PM and PIM markets, but the opportunity for lower production quantities without tooling could shift materials and applications to newer markets that are currently untapped. Over the past two years,

Technology	Description
Binder jetting (3DP)	Selective liquid resin deposition - powder bonding
Material jetting	Droplets of build material selectively deposited
Directed energy deposition	Thermal energy selectively fuses regions of powder bed
Sheet lamination	Focused thermal energy melts materials as deposited
Vat photopolymerisation	Liquid photo polymer selectively cured by light activation
Material extrusion	Material selectively dispensed through nozzle of orifice

Table 1 Additive Manufacturing categories

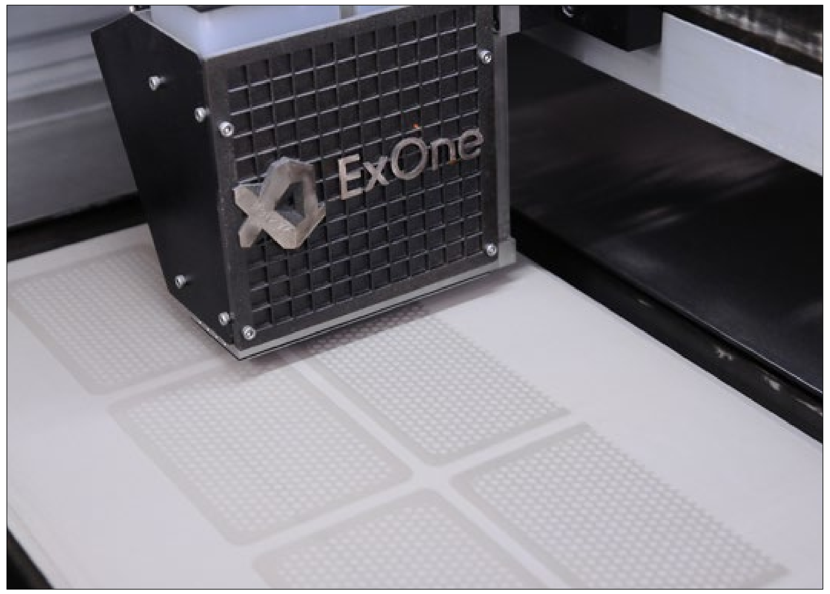

Fig. 3 An ExOne Binder Jetting system printing in a bed of metal powder

Fig. 4 A close-up of the print head on an ExOne Binder Jetting system

Fig. 5 The build volumes of various ExOne machines, showing the achievable build rates

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Fig. 6 The ability to 3D print new metal, ceramic and matrix materials in unique product forms allows for broader application and new market opportunities that are largely untapped

Fig. 7 An SiC part printed in an ExOne M-Flex® system

extensive research has been performed for material qualification within ExOne which, despite the similarities of the process to PM, has shown instances where it excels over conventional powder compaction.

Metals research

Metal printing systems used in Binder Jetting processes initially involved printing a matrix of stainless steel (420 or 316) followed by infiltration with bronze. The resulting material has strength characteristics similar to high-strength, low alloy steel and has been used to produce functional load and heat bearing prototypes for a wide range of industrial and consumer applications.

Infiltrations using additional lower melting point materials such as copper or aluminium provide various application opportunities for the energy, electronics and automotive industries. These could infiltrate with printed parts in tungsten, iron or even ceramics to form matrix composite materials that are traditionally processed using powder blending and forming.

Another unique area of metallic research for ExOne includes the application of binder jetting to the filter markets. Main areas of research include printed 316L and bronze with light sintering to average a 60-70% dense part for metallic filters in the energy and chemical processing industries. The ability to print unique designs and filtration channels can provide better performance efficiency and increase durability over traditionally formed filter methods.

In more recent efforts, however, metallics development has focused on monolithic materials for critical high temperature or corrosion resistant applications. Using a combination of refined powder specifications and innovative sintering methods, ExOne has extended the benefits of Binder Jetting technology to a wide range of materials, including 316 stainless steel, 17-4 PH stainless steel, Alloy IN 625, Inconel 718 and Cobalt-Chrome-Molybdenum. These alloys are printed and sintered to full or near-full density and may be HIPed to remove any residual porosity if necessary for particular applications.

Applications for porous metallic filters, unique metal matrix composites for wear part applications, and full density monolithic materials for automotive, aerospace and oil/gas industries will continue to drive the metal materials development.

Ceramic and carbide research

Non-metallic materials present a unique opportunity for 3D printing of parts using Binder Jetting technology. From a material science perspective, ceramics, carbons and refractory metals are well suited to the Binder Jetting process because of their inherent material properties, which prohibit other 3D printing technologies such as Powder Bed Fusion or Directed Energy Deposition from being technically feasible or economical. For example, nickel-based and ferrous materials commonly used in laser sintering processes melt at temperatures ranging from 1250°C to 1550°C, while materials such as silicon carbide and tungsten carbide have melting points around 2800°C. Ceramics and refractory materials are often difficult to form using conventional manufacturing techniques, which further makes the case for manufacturing using Binder Jetting. In many cases, the Binder Jetting of ceramics can simply replace the shaping operation in an already defined set of process steps that include powder preparation, high temperature thermal treatment and finishing.

"In many cases, the Binder Jetting of ceramics can simply replace the shaping operation in an already defined set of process steps..."

The thermal treatment steps with a printed ceramic are often identical to those currently being used on traditionally prepared preforms. For example, tungsten carbide powder is commonly formed in moulds to form complex geometric parts, which are then infiltrated with metallic materials such as copper. These parts are used in applications that require wear resistance in highly abrasive environments commonly found in the energy and mining industries.

The ExOne Binder Jetting process can eliminate the moulding operation for cost and time savings, while also expanding the design freedom for complex features within the part. To further reduce risk, often the same powders can be utilised in ExOne printers to form the shape and the same alloy used to infiltrate the preform.

Reaction based processing is another commonly utilised ceramic thermal treatment step that can be taken advantage of when combined with a 3DP process. For example, ExOne has successfully printed carbon parts using Binder Jetting techniques and then infiltrated those parts with silicon metal. Upon proper thermal treatment, the combination reacts to become Silicon Carbide. Silicon Nitride can also be reaction bonded by printing silicon powder followed by nitriding in a furnace that results in Silicon Nitride.

Fig. 8 A 420 stainless steel / bronze matrix rotor and stator for down-hole drilling applications

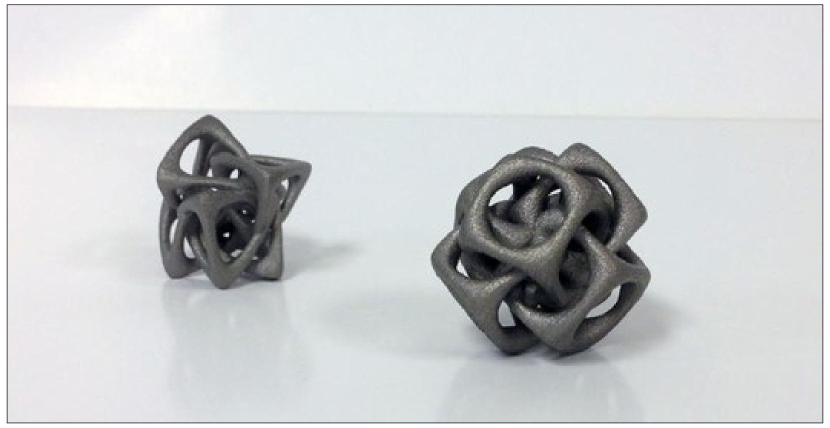

Fig. 9 316L stainless steel decorative parts sintered to a high density

Outlook

The innovation of PIM technology and the emergence of Binder Jetting-based 3D printing provides a unique opportunity for cross collaboration and natural synergies for existing manufacturing operations and post processing heat treatments. The idea of using Binder Jetting as a natural complement and prototyping/series production tool for PIM can help expand the industry's market opportunities.

As manufacturing designs become more complex and mass customisation continues to accelerate speed to market and series production, the need for smaller lot quantities and rapid digital design changes will continue to shift manufacturing operations towards lower production runs of numerous designs. With Binder Jetting, the elimination of tooling while maintaining the traditional product forms of PIM provides the opportunities to focus on these manufacturing shifts and expand the market opportunities into broader industries for both PIM and AM technologies.

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The accurate prediction of surface defects with Powder Injection Moulding simulation

Final surface quality can be a critical issue in the production of Metal and Ceramic Injection Moulded parts, particularly for consumer applications such as watches and smartphones where highly polished surface finishes are required. In the following article Huan-Chang Tseng, from Taiwan's CoreTech System (Moldex3D) Co., Ltd, and his co-authors Chao-Zong Ruan and Shun-Tian Lin, report on the use of process simulation technology to help predict the so-called black line phenomenon that is associated with powder-binder separation and the resultant low powder concentration areas.

Black lines are one of the most critical product quality issues in Metal Injection Moulded (MIM) parts production, particularly with regard to surface quality. Many companies using MIM technology hope to overcome this challenge with an optimised tool. The CAE software tool for plastic injection moulding, Moldex3D, has not only been extended in its capabilities for simulating the MIM process, but can now also provide powder concentration predictions to help manage uniform powder dispersion and powder-binder separation. In this paper, the authors demonstrate a strong correlation between the predicted low powder concentration areas and the real-life black line regions. The simulation method is illustrated and detailed, using a real experiment.

Over the last two decades MIM has become the dominant sub-set of Powder Injection Moulding (PIM) with a broad range of applications, including 3C products, medical implants and aerospace components. MIM is a versatile production technology capable of producing complex three-dimensional structures that are in many cases superior to those achievable using more conventional manufacturing methods.

There are four basic steps in the MIM process: (1) preparation of a well-dispersed granular feedstock with the desired fraction of powder; (2) injection moulding of the feedstock to produce the desired green parts; (3) the debinding process to remove the binder phase from the green parts and (4) the sintering process to obtain the final product.

Black lines are often found on the surface of the final products, which typically show some dark

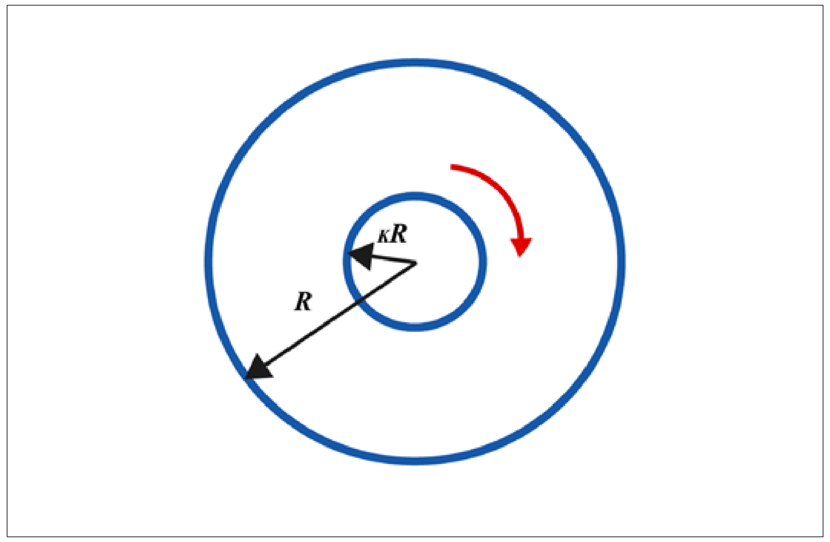

Fig. 1 Illustration of Couette flow field

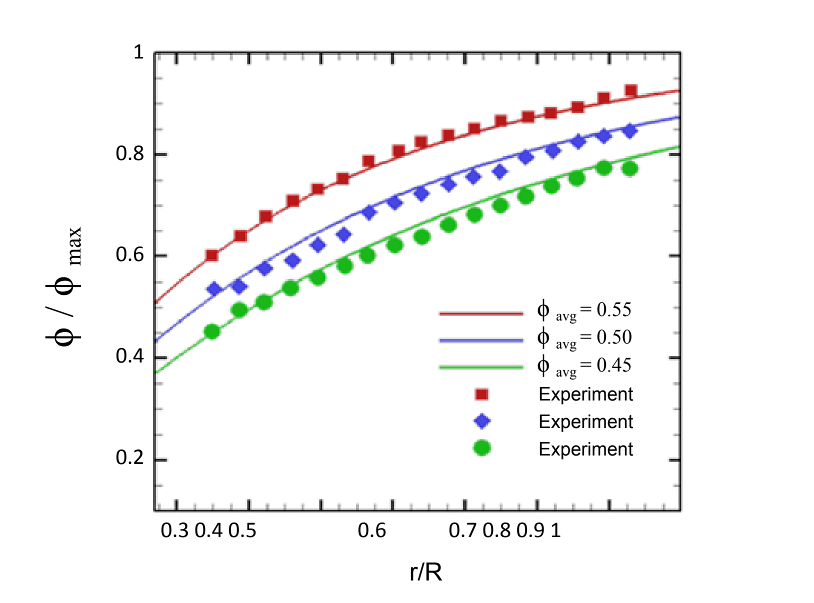

Fig. 2 Dimensionless volume fraction against different average volume fractions

areas among a larger light area. This usually occurs in the vicinity of the gate. Such a defect is due to the powder-binder phase separation or an elevated binder concentration. However, predicting phase separation or powder/binder concentration is critical in avoiding black line issues.

Most of the general concepts in Metal Injection Moulding are derived from thermoplastic injection moulding. For many years, 3D injection moulding simulation software from Moldex3D has become well known as a powerful tool in the thermoplastic industry. Moldex3D has been extended not only to simulate MIM processing, but to also provide powder concentration prediction to present uniform powder dispersion and powder-binder separation. The aim of this paper is therefore to introduce the concept of powder concentration prediction in mould filling via the Moldex3D PIM package.

Detail of the simulation

Flow governing equation

MIM feedstock is a concentrated suspension mixture, consisting of powder and binder, and is assumed to be a Generalised Newtonian Fluid (GNF). A set of governing equations to describe the transient and non-isothermal fluid behaviours for channel flowing and mould filling are addressed below:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 , \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u} - \boldsymbol{\sigma}) = \rho \mathbf{g} , \quad (2)$$

$$\boldsymbol{\sigma} = -p\mathbf{I} + \eta(\nabla \mathbf{u} + \nabla \mathbf{u}^T) , \quad (3)$$

$$\rho C_P\left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T\right) = \nabla \cdot (k \nabla T) + \eta \dot{\gamma}^2 , \quad (4)$$

where ρ is density; $\mathbf{u}$ is velocity vector; t is time; $\boldsymbol{\sigma}$ is total stress tensor; $\mathbf{g}$ is acceleration vector of gravity; p is pressure; η is viscosity; C_p is specific heat; T is temperature; k is thermal conductivity; $\dot{\gamma}$ is shear rate. The Finite Volume Method (FVM) is employed to solve the transient flow field in a three-dimensional geometry with complexity thanks to its robustness and efficiency.

Powder concentration equation

The suspension balance model, developed by Morris and Boulay [1], is considered for the suspension flow of rigid spherical particles in a Newtonian fluid. The particle phase is approximated as a pseudo-continuum. The dominant interaction between the particles involves hydrodynamic, viscous, and non-Brownian forces with no external field except gravity.

Averaging over the particulate volume and dividing by the particle density yields the particle-phase conservation equation,

$$\frac{\partial \phi}{\partial t} + \langle \mathbf{u} \rangle \cdot \nabla \phi = -\nabla \cdot \mathbf{j}_{\perp} , \quad (5)$$

$$\mathbf{j}_{\perp} = \phi(U - \langle \mathbf{u} \rangle) , \quad (6)$$

where ϕ is the particle volume fraction, $\langle \mathbf{u} \rangle$ is the suspension average velocity, $\mathbf{j}_{\perp}$ is the particle flux relative to the mean suspension motion, and U is the local average velocity of the particulate phase.

Averaging the general momentum balance over the particle phase and restricting attention to low Reynolds numbers and neutrally buoyant, mono-disperse spheres yields the relation for the particle flux,

$$\mathbf{j}_{\perp} = \frac{2a^2}{9\eta_f} f(\phi) \nabla \cdot \Sigma_p , \quad (7)$$

where a is the particle radius, η_f is the viscosity of the suspending fluid, $f(\phi)$ is termed a sedimentation function, and Σ_p is the particle stress.

The sedimentation function is described in Richardson and Zaki [2], taking

$$f(\phi) = (1 - \phi/\phi_{\max})(1-\phi)^{\alpha-1} , \quad (8)$$

where $\phi_{\max}$ is maximum packing fraction and α is a index of particle friction.

The particle stress Σ_p contains both shear and normal stress portions,

$$\boldsymbol{\Sigma}_p = 2\eta_f \eta_p(\phi)\mathbf{E} - \eta_f \eta_n(\phi)\dot{\gamma}\mathbf{Q} , \quad (9)$$

where η_f is the suspension fluid viscosity, η_p is the shear stress viscosity, η_n is the normal stress viscosity; $\mathbf{E}$ is the rate-of-strain tensor, $\dot{\gamma} = \sqrt{2\mathbf{E}:\mathbf{E}}$ is the magnitude of rate of strain; $\mathbf{Q}$ is a anisotropic tensor.

The shear and normal stress viscosity are given in a dimensionless volume fraction of $\bar{\phi} = \phi / \phi_{\max}$,

$$\eta_p(\phi) = 2.5\phi_{\max}(1-\bar{\phi})^{-1} + K_s\bar{\phi}^2(1-\bar{\phi})^{-2} \quad (10)$$

$$\eta_n(\phi) = K_n\bar{\phi}^2(1-\bar{\phi})^{-2} , \quad (11)$$

where K_s = 0.1 and K_n = 0.75, is a factor fit to match experimental data of wide-gap Couette flow.

The anisotropic tensor $\mathbf{Q}$ is a constant tensor, which describes the anisotropy of the normal stresses,

$$\mathbf{Q} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} , \quad (12)$$

where λ_1, λ_2, and λ_3 are characteristic values for curvilinear flows.

Validation of powder concentration

As a validation, the suspension balance model was used to calculate powder concentration and the calculated results were compared with related experimental data [3]. In a simple wide-gap Couette flow field, confined between two concentric cylinders, the experimental powder concentration of volume fraction is measured by using nuclear magnetic resonance (NMR) imaging for nearly mono-disperse concentrated suspensions of spherical non-colloidal particles, as shown in Fig. 1.

These experimental powder concentration data [3] involve three average volume fractions, ϕ_{avg} = 0.45, 0.55, and 0.5, for PMMA spheres (with an average powder diameter of 675 µm) immersed in Newtonian oil. In the Couette flow, the stationary outer cylinder radius is R (2.38 mm) and the rotating inner cylinder radius is kR (0.64 mm) with an angular velocity of 17-117 rpm, yielding shear rate about 1-25s^{-1}. The length of the cylinder is 25 mm. Details of experiments are available elsewhere [3].

The experimental data were used for comparison of predictions with the maximum fraction of $\phi_{\max}$ = 0.68. Fig. 2 shows the reduced volume fraction distribution $\phi/\phi_{\max}$ through the reduced radius r/R between the inner and outer cylinders. As a result, the agreement between the experiments and predictions are shown to be excellent. Clearly, this indicates that the suspension balance model is available for predicting powder concentration. Furthermore, a low concentration occurs near the rotating inner cylinder due to high shear rates, whereas high concentration is found near the stationary outer cylinder, due to low shear rates.

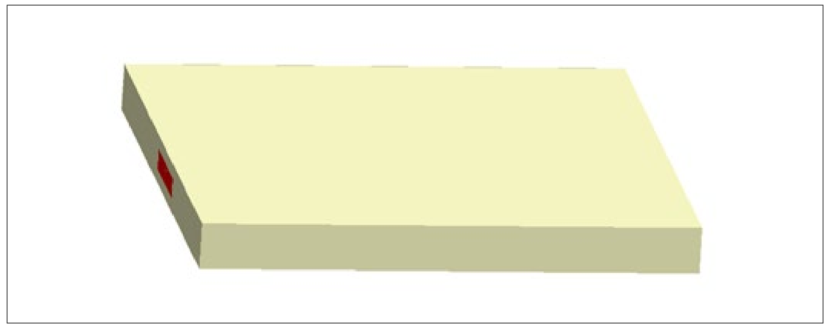

Fig. 3 The plaque geometric illustration with 16 x 16 x 1.5 mm³

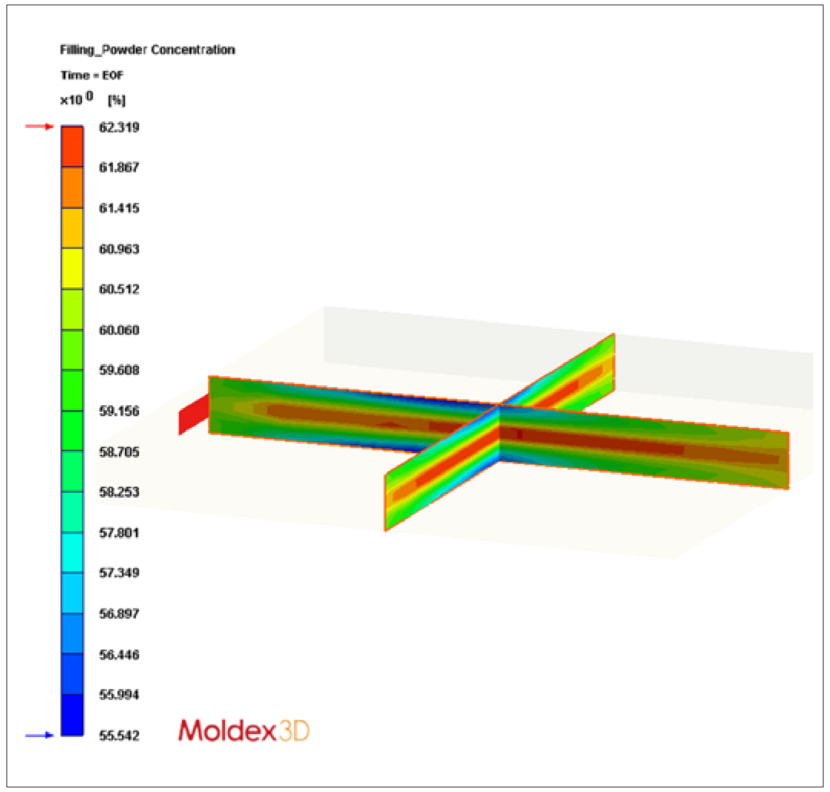

Fig. 4 Powder concentration pattern for the plaque filling with the average volume percent of 60 vol.%

Powder-binder phase separation

Physically, shear-induced variation in powder concentration is known as shear-induced particle migration for suspension rheology. Particle migration generates a powder concentration gradient. The concentration is inversely proportional to the shear rate. This is also deemed as a powder-binder phase separation phenomenon.

Application to simple flow channels

The assessment of powder concentration has been validated. Here, further use is made of the suspension balance model for the concentrated suspension fluid in simple flow channels, including both *plaque* and *contraction-expansion* geometries, wherein the average volume percent is 60 vol.%, and the powder diameter is 10 µm. The goal is to describe the

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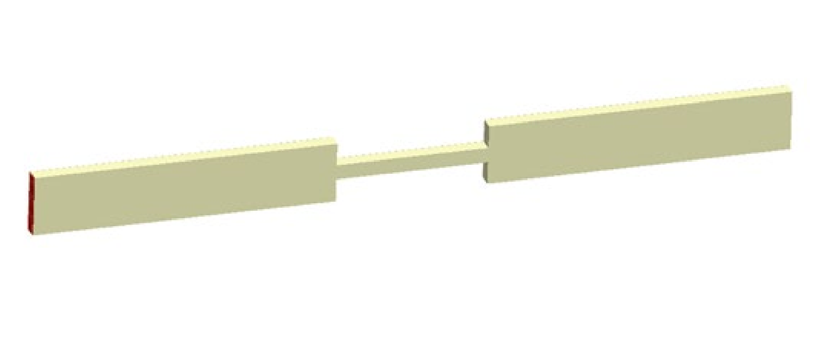

Fig. 5 The 4:1:4 contraction-expansion geometric illustration with the biggest size of 4 mm and smallest size of 1 mm

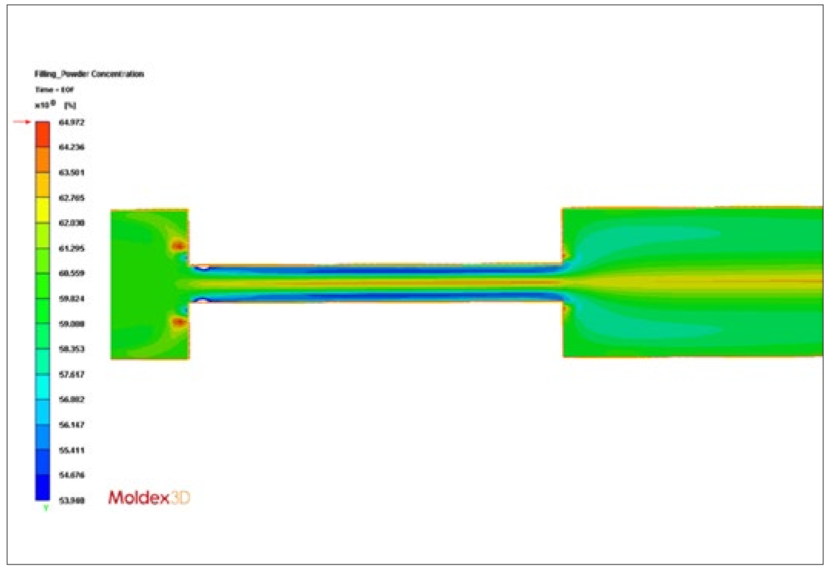

Fig. 6 Powder concentration pattern for tensile-bar filling with the average volume percent of 60 vol.%

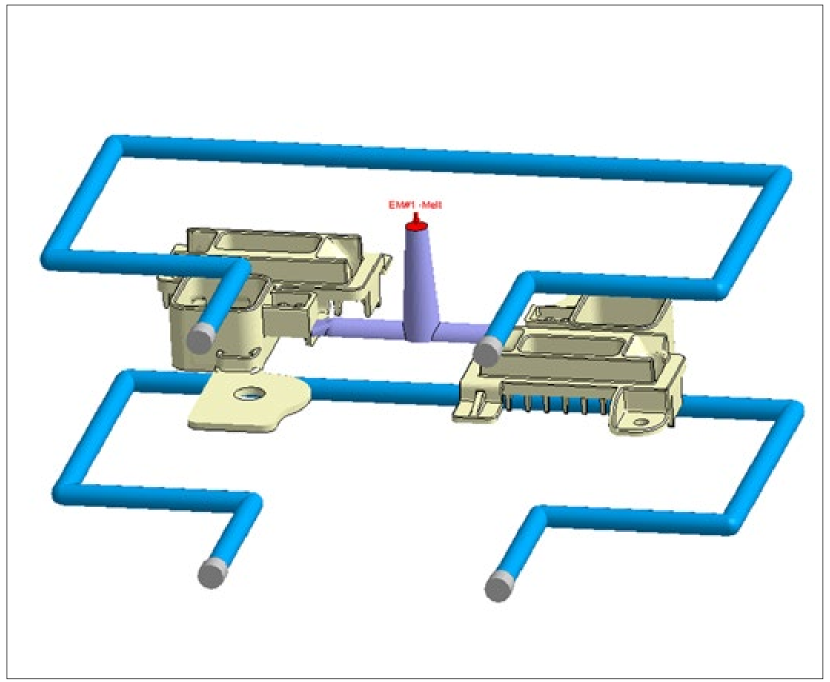

Fig. 7 Geometry of the real MIM part

powder-binder phase separation during flow.

The 16 mm x 16 mm x 1.5 mm plaque geometry is illustrated in Fig. 3. Fig. 4 shows the powder concentration pattern in the plaque flow. The appearance of a powder concentration gradient is obvious. As a whole, near a wall, the concentration is relatively low, whereas the central concentration is high. For this reason, such a representation clearly indicates powder-binder phase separation [4-5].

In addition, the schematic diagram for the 4:1:4 contraction-expansion geometry is given in Fig. 5, wherein the contraction size is 1 mm and the expansion size is 4 mm. Fig. 6 shows the concentration profile. In the plaque, an obvious concentration gradient is also exhibited. There are several interesting findings for the contraction-expansion flow. When the fluid flows into the contraction part, maximum concentration obviously occurs in the proximity of the corner of the inlet expansion part. In particular, the contraction concentration pattern is very vivid from the low wall concentration to the high central concentration, namely, strong phase separation. Through the contraction, the concentration gradient is relatively weak for the outlet expansion.

Application to a real MIM part

The real part of interest was considered in Fig. 7. The part volume is about 4 cm^3. The MIM material used in this work consisted of a POM (Polyoxymethylene) binder and a steel powder, trade name Catamold 17-4 PH, and was supplied by BASF. The average powder concentration was about 60 vol%. The mould temperature was held to approximately 100°C, while the inlet temperature was 200°C. The filling time and packing time were around 0.3 seconds and 2.3 seconds respectively. Note that the green part mass was around 23 g and the sintered part was around 21 g.

As a result, Fig. 8 shows that the surface defect on the green part exhibits some dark lines among the

Fig. 8 The black lines are visible on the real green part

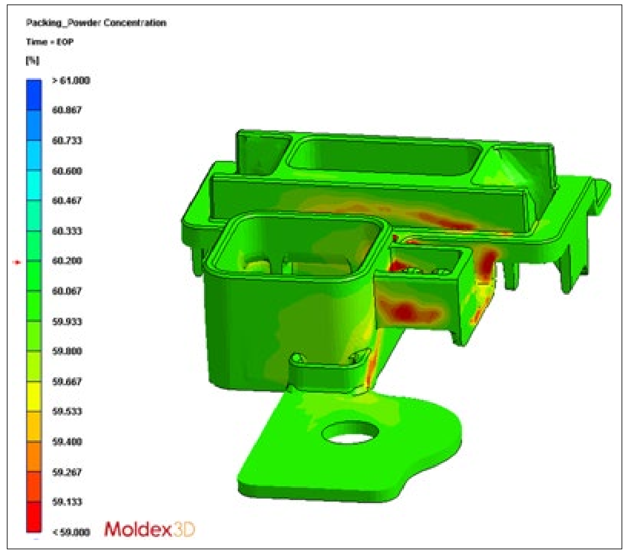

Fig. 9 Powder concentration distribution prediction

larger light areas. This is generally called a black line in industrial MIM fabrication, or is known as powder-binder phase separation for the academic community.

Furthermore, the surface powder concentration distribution was predicted by the Moldex3D's PIM package, as shown in Fig. 9. It is clear that the overall distribution is uniform or is close to the average concentration (60 vol %). Obviously, some lower concentration areas can be noticed. One can further compare the relationship between Figs. 8 and 9. Surprisingly, the black lines are related to low concentration. Therefore, the black lines on the green part in the MIM process might indicate a high binder concentration or a low powder concentration. This is helpful in suggesting black line generation via the powder concentration prediction, especially concerning surface defects in MIM fabrication.

Conclusion

In this work, the importance of performing powder concentration simulation of the concentrated suspension fluids has been demonstrated. Based on the powder concentration simulation, black lines or powder-binder phase separation of the green parts in MIM processing can further be predicted, particularly near gate locations. There is a good correlation between the numerical and experimental results, indicating that the powder concentration scheme on the green part successfully determine black lines for the real sintered products. Therefore, this simulation system, including the suspension balance model and Moldex3D, could be a useful tool for MIM mould designers.

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