Vol. 8 No. 4 DECEMBER 2014

FOR THE METAL, CERAMIC AND CARBIDE INJECTION MOULDING INDUSTRIES

# POWDER INJECTION MOULDING INTERNATIONAL

## in this issue

**MIM in the firearms industry**

**Dynacast International**

**Transitioning from plastic to metal**

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For the metal, ceramic and carbide injection moulding industries

# Firearms: US slowdown fails to dampen optimism

The firearms industry is an important market for MIM, accounting for significant levels of production in North America and, to a lesser extent, in Europe and Asia. It is an industry that encompasses both civilian, law enforcement and military markets and as such it is subject not only to consumer trends, but to national and international political events.

Despite the current slowdown in the US firearms market, widely interpreted as an inevitable market correction following a period of dramatic growth, MIM producers are optimistic about the technology's future potential in this sector. Our report on MIM in the firearms industry (page 31) clearly demonstrates the extent to which firearms manufacturers have embraced MIM technology.

We also profile one of the newest entrants into the MIM business, Dynacast International (page 49). There is no doubt that Dynacast has ambitious growth plans and, since its acquisition of Kinetics in October, the company now has expertise in both its unique variant on the MIM process and in conventional MIM tooling and moulding technology.

Many entrants into the MIM industry come from the plastic injection moulding industry. For these companies the adoption of MIM can be a daunting challenge. With plastics, injection moulding is the end of the process, in MIM it's just the start. Dr Satya Banerjee shares some of his extensive experience as a MIM industry consultant (page 55).

Looking ahead to 2015, there is an exciting range of PIM related conferences, courses and exhibitions on the horizon. For the MIM community the year kicks off with the MIMA's MIM2015 conference, this year located in Tampa, Florida. For those who haven't attended this annual conference, it is an event that provides a unique platform at which to network and exchange ideas with many of the leading figures in the US MIM industry - we hope to see you there!

Nick Williams
Managing Director and Editor

**Cover image**
*2014 Design Excellence award winning MIM parts manufactured by AFT, an ARCMIM Company and used in a Smith and Wesson rifle (Courtesy MPIF)*

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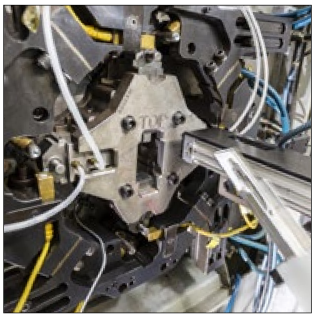
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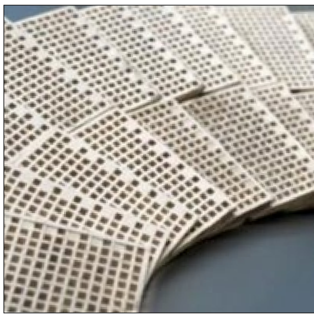
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# Regular features

# Industry News

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

## Phillips-Medisize expands MIM facilities

Phillips-Medisize Corp., USA, is undertaking a $30 million expansion at five facilities throughout Wisconsin in a move that is expected to create nearly 500 new jobs. The company's MIM facility in Menomonie will expand to nearly 4700 m$^2$. Phillips stated that the expansion allows for the installation of ten additional injection moulding machines and a new continuous debinding and sintering furnace. This will be the second expansion of the facility in the last two years and makes a total of four continuous and three batch furnaces at the site.

The expansion drive will also see a 3000 m$^2$ addition at Phillips-Medisize's medical facility in New Richmond. This will include the construction of additional clean room space due to the facility's focus on the manufacturing and assembly of diagnostic and surgical products. Construction is expected to be complete in late 2015.

Phillips-Medisize states that it also plans to add more experienced personnel to its Design Development Centre staff over the coming months. These individuals, stated the company, will be experienced design and development professionals who will assist in the commercialisation of pharmaceutical devices, allowing Phillips-Medisize to continue to provide its customers all the resources necessary to take a drug delivery device from the bench to the patient's bedside.

To help secure the new jobs, the Wisconsin Economic Development Corporation (WEDC) has authorised Phillips-Medisize to receive up to $5 million in state tax credits over 39 months. The actual amount of tax credits the company will earn will be contingent upon the number of jobs created. "Phillips-Medisize is already a major employer in Wisconsin with 1,400 employees at twelve facilities throughout the state. An investment of this magnitude really solidifies this growing company's commitment to Wisconsin," stated Scott Walker, Governor of Wisconsin. "Phillips-Medisize has operations around the world and had other options for this expansion. Their decision to stay and grow here says a lot about the state's strong business climate and dedicated workforce."

Phillips-Medisize has already started construction at facilities in New Richmond and Menomonie, and future expansions are planned at its facilities in Hudson, Phillips, Medford and Eau Claire. "Phillips-Medisize has a laser focus on supporting our customer's growth and the company's new business awards through continued investment in our people, process and facilities," said company Chairman and CEO Matt Jennings. "We are excited to announce the investments in our facilities that will expand our capabilities, enable us to hire employees with needed expertise and will allow us to deliver on our commitments to our customers with the right resources, at the right time."

www.phillipsmedisize.com


## Critical Process Parameters in MIM Sintering Furnaces

The accuracy of dimensional tolerances of sintered MIM parts is limited, especially in the case of larger geometries. One reason is green density fluctuations introduced during high-pressure injection molding leads to inhomogeneous shrinkage behavior at elevated sintering temperatures. Another reason is large temperature gradients in the furnace hot zone cause geometrical distortions, even in part areas with rather homogenous density distributions.

By examining different factors for determining unwanted temperature gradients in MIM vacuum furnaces, we are able to evaluate the process parameters and present possible improvements by utilizing tight control and accurate design of heating elements and hot zones, as well as advanced process gas management systems, for commercial use in large series production environments.

Find out about critical process parameters for MIM sintering heat treatment furnaces, testing results and more by visiting the link below.


Ipsen's TITAN DS furnace is now available in a smaller size, specially designed for titanium and other high alloy materials.

- High temperature capabilities up to 3,000 °F (1,640 °C)
- All-metal or graphite hot zones are available
- 18" x 18" x 24" (457 mm x 457 mm x 610 mm) work zone

**Ipsen also offers debinding and sintering furnaces in a variety of larger sizes.*

**Visit IpsenUSA.com/Critical-Process-Parameters to view the full technical presentation.**

Ipsen

## AMS increases capacity for Metal Injection Moulded Ti parts production in Australia, targets US market

Advanced Metallurgical Solutions (AMS), the only Australian manufacturer of Metal Injection Moulded (MIM) components and sintered metallic membrane, has announced that an additional 100 tonne automated injection moulding machine and an additional vacuum/hydrogen sintering furnace, as well as ancillary equipment, will be brought online in the first quarter of 2015. The investments have been made as part of the formation of a dedicated titanium manufacturing division. Bringing the equipment online will increase the company's average weekly capacity in titanium by 24,000 MIM components or 150 $m^2$ of metallic membrane.

Craig Erskine, Director of Development at AMS, told *PIM International*, "We see an increasing trend towards using titanium components thanks to the efficiencies of the advanced manufacturing techniques we use. Complex parts can be made quickly with high consistency, high strength, tight tolerances and almost no waste. These efficiencies bring the cost of titanium components down several fold, making them competitive with components made of inferior materials using traditional methods."

A dedicated titanium injection moulding division opens new opportunities for customers requiring production runs smaller than the minimum 1,000 to 4,000 parts required by many MIM manufacturers, stated Erskine. "Pooling groups of similar components allows much of the variable cost to be spread over several smaller runs, bringing the component cost of runs of 50-100 components in line with the cost of much larger runs. Once the 3D printed or machined prototyping phase for a component is complete, AMS can offer substantial savings in both low and high volumes."

"This opportunity should also be of interest to potential small and medium run customers in the USA," explained Erskine, "since there is no customs duty for titanium goods imported into America from Australia and no language barrier either. These factors help make switching to titanium MIM with us easier and more economical."

AMS also manufactures MIM components from stainless steels and superalloys. The company works together with Australian universities to push the boundaries in filtration technology and component manufacturing.

www.ams100.com

## Powder Injection Moulding Short Course to be held in Barcelona

The European Powder Metallurgy Association's EuroMIM sectoral group has announced that it will be organising a Powder Injection Moulding Short Course from April 15–17 2015 in Barcelona, Spain.

The course is aimed at potential users of PIM technology, as well as technical and managerial personnel from the PIM industry who may be seeking a more comprehensive understanding of PIM's capabilities and applications. An optional visit to one of Spain's leading PIM R&D laboratories at Universidad de Castilla-La Mancha, Ciudad Real, is also planned prior to the course.

The course will cover both Metal Injection Moulding (MIM) and Ceramic Injection Moulding (CIM).

Confirmed presentations at the time of publication include:

- **Introduction to Metal Injection Moulding**
  *Dr Marco Actis Grande, Politecnico di Torino, Italy*
- **Powder Manufacture**
  *Keith Murray, Sandvik Osprey Ltd, UK*
- **Raw Materials: Feedstock**
  *Martin Bloemacher, BASF Germany*
- **Injection Moulding/Micro Moulding**
  *Speaker TBC*
- **Ceramic Injection Moulding**
  *Prof Lars Nyborg, Chalmers University, Sweden*
- **Debinding**
  *Dr Gemma Herranz, UCLM, Spain*
- **Sintering Options**
  *Ingo Cremer, Cremer GmbH, Germany*
- **Design Criteria**
  *Dr Thomas Hartwig, Fraunhofer IFAM, Germany*
- **Secondary Operations**
  *Peter Vervoort, Eisenmann GmbH, Germany*

The registration fee includes accommodation for two nights at the Tryp Apolo Hotel, all relevant course documents, refreshments and a course dinner on the evening of April 16. A reduced registration fee is available for academics from European universities, and there are substantial discounts for EPMA members. The organisers state that space is limited and early booking is highly recommended.

www.epma.com/shortcourse



### Submitting News

To submit news to *Powder Injection Moulding International* contact Nick Williams: nick@inovar-communications.com

## Kalashnikov signals further expansion of MIM technology usage following acquisition of Sintez

In Spring 2014 it was announced that firearms producer Kalashnikov Concern, part of the Russian state corporation Rostec, was to purchase 51% of the shares in Russian Metal Injection Moulding (MIM) parts producer Sintez (Synthesis-PD). Kalashnikov has since re-stated its commitment to adopt MIM technology as part of a major capacity expansion and efficiency drive. The cost of the deal announced earlier this year, reported to be financed from Kalashnikov's own capital, is more than RUR 250 million (US$ 7.1 million).

Kalashnikov Concern's CEO Aleksey Krivoruchko commented at the time of the announcement, "Partnering with Synthesis-PD is an important step in the modernisation of the entire enterprise's production. Currently, 90% of parts are produced and refined manually, using old technologies that require significant time and effort. Thanks to the experience of Synthesis-PD, we will be able to cut the time required to manufacture parts in half and reduce production costs by more than 40%, as well as improve quality and increase production rates."

*The Kalashnikov AK-74 (Photo Rostec)*

Almost RUR 5 billion ($126 million) is to be invested in modernising the Kalashnikov Concern by 2017, according to Rostec's Sergei Chemezov. ■

## Changes announced at Carpenter

Carpenter Technology Corporation's Board of Directors has announced that Gregory A Pratt will return as CEO of the company, replacing Bill Wulfsohn. Pratt was Carpenter's CEO in 2009 - 2010 and has been a Board member since 2002. He will continue as the Chairperson of Carpenter's Board, a position he has held since 2009.

Wulfsohn, who resigned to take another role outside of the company, will step down from the CEO role and Board of Directors immediately, but will assist the company in a transition support role until December 31, 2014. "It has been a pleasure to work with Bill. Together, we have accomplished a great deal," stated Pratt. "We wish Bill well in his next endeavors and thank him for his outstanding leadership and service to Carpenter."

www.cartech.com ■

## Miniature tool set that helps promote MIM wins 2014 JPMA award

Japanese MIM producer Castem Co. Ltd. has received a JPMA award for a miniature tool set manufactured by MIM. Whilst there have been many decorative miniature tools produced, for example for key chains or accessories, these are non-functional and the materials used to make them are silver, or die-cast aluminium or zinc, making them far from being real tools. Castem has not only given these complex tools full functionality, but they are also manufactured using authentic tool materials such as stainless steel and tool steel.

Product development for the miniature tool set was carried out by the company's experienced engineers who carefully designed the moulds for the eleven tools. The parts were manufactured by MIM and assembled in Castem's MIM facility. The material used for the micrometer and callipers is SUS630, equivalent to 17-4. SKD11, equivalent to D2 tool steel, was selected for all the others tools.

The tool set has had significant exposure on TV and in newspapers in Japan and has contributed to an increase in public awareness of MIM. The set includes a micrometer, scissors, needle nose pliers, hacksaw, water pump pliers, wire cutters, machine vice, callipers, adjustable wrench, pliers and a C Clamp.

www.castem.co.jp
www.jpma.gr.jp


*Miniature MIM tool set manufactured by Castem Co. Ltd. (Image JPMA)*

# LÖMI relocation doubles production and research capacity

LÖMI, a market leader in solvent debinding furnaces for the PIM industry based in Aschaffenburg, Germany, has invested €2.5 million in new facilities, more than doubling its capacity for R&D and equipment production. Christian Ferreira Marques, Managing Partner at LÖMI, told *PIM International*, "The company has made this investment in order to meet the increasing demand for new technologies and processes as many PIM parts producers follow an ongoing trend in the industry of changing from conventional debinding technologies to organic solvent debinding."

The company has only moved 10 km from its previous location to new larger premises which will allow for further expansion. "The decision to relocate has even at this early stage proved to be the right decision. Whilst construction of the new facilities was still under way it became clear that further expansion would be necessary and as a result we have already constructed a second manufacturing hall," stated Ferreira Marques.

The new buildings were designed to achieve a high level of energy efficiency with all heating generated by heat pump technology. LÖMI also invested in state-of-the-art technology for design engineering and production. "To optimise our material flow, we purchased a fully automatic vertical storage lift by SSI Schäfer to gain 170 m² of storage space for small parts alone. By integrating this into our enterprise resource planning, we are able to reduce response and lead times for our customers," stated Ferreira Marques.

Since its formation in 1991, LÖMI, an owner-managed company, has been a pioneer in environmental technology. Its PIM solvent debinding furnaces are recognised as being environmentally friendly as the solvent used for extracting the binder systems is operated in a closed system. The solvent is completely recycled in an integrated or attached LÖMI solvent recovery system. The company also

*An impression of LÖMI's new manufacturing and R&D facilities facilities close to Aschaffenburg*

offers these solvent recovery units as stand-alone systems for numerous industrial sectors including automotive, aerospace, chemical, optical, electronics, printing, medical and pharmaceutical.

One of the company's traditional strengths has been research and development as a third of its staff are engineers. It is frequently approached by German universities and numerous institutes, including several Fraunhofer institutes, to develop various research projects. Most recently, LÖMI has met current challenges in technology and developed new processes and plants for plastics recycling. The company's innovation and environmental research was recognised by the regional German government through the granting of money for the company's investments in its new larger facilities.

With regard to the PIM industry, the company will increase the number of its rental debinding furnaces so that customers can perform in-house testing at their own facilities. The company offers comprehensive know-how along the entire PIM process chain, from research and development to design engineering, production, commissioning and after-sales-service. "Over the years, we have set many standards in the industry, and with these new facilities we will be able to meet our customers' requirements in yet even higher quality," concluded Ferreira Marques.

www.loemi.com

## AP&C achieves AS9100 certification

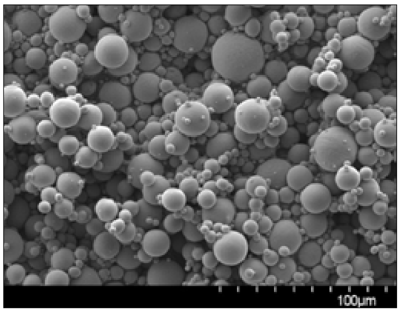
AP&C Advanced Powders and Coatings Inc. (AP&C), based in Boisbriand, Canada, has announced that the company's quality management (QM) system is now AS9100 certified. The company stated that with the new certification it is better positioned to service its aerospace customer base as they move from R&D to production of aircraft components using Metal Injection Moulding (MIM), Additive Manufacturing (AM) and other Powder Metallurgy processes.

AP&C specialises in the production of high purity spherical powder of titanium and other reactive metals by plasma atomisation. Its powders are used in a wide range of PM applications including AM, MIM, Hot Isostatic Pressing (HIP) and coatings.

"It's another exciting milestone achievement for our company which is dedicated to producing spherical metal powders from high melting point alloys using its proprietary plasma atomisation systems. We supply our titanium, nickel superalloys and other special products to a growing biomedical and aerospace customer base," stated Jacques Mallette, CEO.

"AP&C is a quality focused organisation that prides itself in consistently enhancing its QM system in order to offer superior quality products and service to its demanding customer base," added Mallette.

www.advancedpowders.com




*SEM of AP&C plasma atomised Ti-6Al-4V powder (0-25 µm)*

## Powder Metallurgy Review: Winter 2014 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 an Introduction to Metallography for PM, a report on a recent visit to the UK's Atomising Systems Ltd, and technical reports from the PM2014 World Congress and AMPM conference in Orlando. *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

## CMG technologies invests for growth in MIM titanium parts production

UK based MIM specialist CMG Technologies has taken delivery of a new sintering furnace which, states the company, will enable it to manufacture complex components from a variety of new materials including titanium. Purchased through a business grant awarded by New Anglia LEP, the new ECM Technologies furnace was delivered to CMG's manufacturing facility in Rendlesham, Suffolk, earlier this month and has already been put to good use with the innovative production of titanium components.

Investment in the new furnace means CMG Technologies now has the in-house capability to manufacture complex components using precious metals such as titanium at a fraction of the cost compared to conventional manufacturing methods. This is achieved by only using the material required to manufacture the component to a net shape, eliminating costly machining and the production of scrap metal.

CMG's development of MIM titanium was originally achieved through a joint collaboration with Johnson Matthey and Sheffield University. The company manufactures its own MIM feedstock in-house. Phil Marsh, Technical and Production Director, stated, "Our collaboration with Johnson Matthey and Sheffield University was a great success, resulting in titanium components with an excellent surface finish of RA 0.6 µm and a high density of 95%."

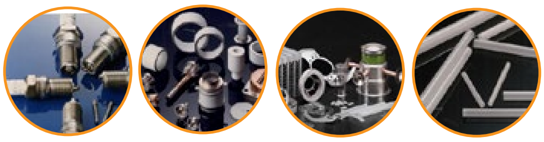
"Following our investment in the new furnace, we will now be able to produce high quality titanium components in-house, facilitating business growth as we access a diverse range of new markets looking to invest in a high commodity, light weight metal at significantly reduced costs."

*The new ECM Technologies vacuum furnace will be used to process MIM titanium components*

As well as cost savings, CMG states that its customers will also benefit from the metal's strength, durability and biocompatibility, which is particularly desirable for a wide range of applications in the aerospace, automotive and medical sectors. Rachel Garrett, CMG Technologies' Sales & Marketing Director, stated that the company's customer base has increased by 56% in recent years.

www.cmgtechnologies.co.uk





## Centorr Vacuum to supply ARCMIM

Centorr Vacuum Industries (CVI), Nashua, New Hampshire, USA, has announced that it will be building a new MIM-Vac M900 debind and sintering furnace for FloMet LLC, an ARCMIM Company. This order, stated CVI, further expands its MIM customer base. FloMet has selected the CVI furnace to process new materials that will be manufactured in its Deland, Florida, facility where it produces a wide range of components for industries including orthodontics, firearms, medical, automotive and aerospace.

CVI has over 30 years of MIM furnace building experience and the new MIM-Vac M (modular) has a number of new design improvements such as an advanced molybdenum hot zones with wide-flow gas-plenum retorts using Sweepgas™ technology for consistent debinding.

www.centorr.com

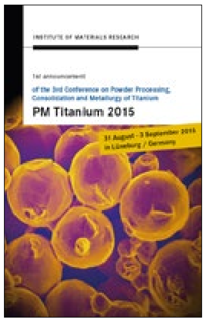
## International PM titanium conference heading to Germany in 2015

The organisers of PM Titanium 2015, the Third Conference on Powder Processing, Consolidation and Metallurgy of Titanium, have announced that the event will be held at the Leuphana University of Lüneburg, close to Hamburg, Germany, from August 31 to September 3, 2015.

PM Titanium 2015 follows successful conferences in Brisbane, Australia (2011) and Hamilton, New Zealand (2013). It will focus on the powder metallurgical processing of titanium and titanium alloys, discussing the status and progress on relevant topics such as:

- Powder production
- Cost reduction
- Microstructure
- Additive Manufacturing
- Intermetallic titanium aluminides
- Metal Injection Moulding
- Pressing, HIP
- Optimisation of properties
- PM biomaterials
- Specific applications and techniques

The conference will be co-chaired by Dr Thomas Ebel and Prof Florian Pyczak of Helmholtz-Zentrum Geesthacht, Germany. The schedule will include the opportunity to visit neighbouring institutes and companies working in the field of titanium powder processing. A call for papers and further information will be published in due course.




www.hzg.de/pmti2015

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## Ceramic Injection Moulding success for dental implants and tools

At present the majority of inserted dental implants are manufactured from titanium. It is anticipated, however, that ceramic implants will increasingly be used in the future, especially when patients suffer intolerance reactions to metallic titanium. Ceramic Injection Moulding (CIM) is already being successfully used to mass-produce high performance zirconia dental implants, which have proved to be an excellent alterative to titanium. In addition to being metal-free, the zirconia-5 mol% yttria ceramic material is also reported to be highly resistant to acids, and the combination of a zirconia CIM implant and a porcelain crown makes them difficult to distinguish from natural teeth.

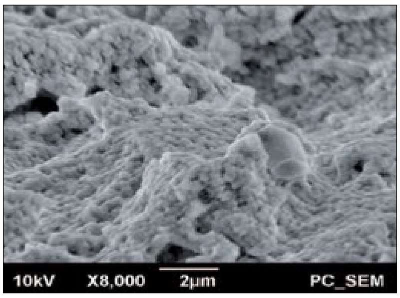

*Fig. 1 The specially developed Maxon dental surface structure on the CIM implants guarantees optimum osseointegration and matches that of etched titanium implants*

Creamed GmbH of Marburg, Germany, has developed its range of single or two-piece zirconia implants called OMNIS with the CIM implant components manufactured by Maxon Dental, a Division of Maxon Motor based in Sexau, Germany. The ceramic dental implants are biocompatible and biologically neutral thereby avoiding any allergic or foreign particle reactions with the jaw bone or gum tissue. Maxon Dental has developed a special surface structure on the CIM implants which allows rapid and secure osseointegration of the living bone tissue into the implant. The surface structure is produced during


*Fig. 2 Single and two-part ceramic injection moulded OMNIS dental implants*

*Fig. 3 The ceramic injection moulded drill bits are exceedingly sharp and suffer practically no wear even after 100 uses*

the injection moulding stage and is similar to the etched surface of titanium implants.

OMNIS CIM implants are produced at Maxon Dental from a yttria-stabilised tetragonal $ZrO_2$ powder mixture having average particle size of 0.3 micron. After debinding at 120°C in a protective atmosphere, the CIM implants are sintered at 1500°C to a density of 6.05 g/cm³. CIM allows special characteristics to be designed into the implant, such as the special textured surface, round thread and thread runout below the crestal level, resulting in mechanical strength comparable to that of titanium implants. A modulus of elasticity similar to that of steel and high flexural strength reduce the risk of implant fracture. The sintered $ZrO_2$-yttria material is said to have a hardness of 1350 HV and bending strength of 800 – 1200 N/mm².

The rigidity of this new material is two to three times greater than $Al_2O_3$. The tetragonal phase of the $ZrO_2$ is kept stable at room temperature by the addition of yttria.

In addition to CIM zirconia dental implants, Maxon Dental also produces CIM dental drills, scalpels and tweezers. CIM zirconia dental drill bits are exceedingly sharp and suffer practically no wear. Even after a hundred uses the cutting edges do not become blunt whilst conventional steel drills already start to lose their sharpness after twenty operations.

www.creamed.de

www.maxonmotor.com

## Euro PM2015 Call for Papers issued

The European Powder Metallurgy Association, organiser of Euro PM2015 Congress, has issued a Call for Papers for the event. Euro PM2015 will be held at Reims Congress Centre, France, from October 4-7, 2015. Authors wishing to submit abstracts for consideration in the technical programme should do so by February 15, 2015.

Europe's annual PM gathering will include a programme of plenary and keynote addresses, oral and poster presentations. Special interest seminars will focus on Additive Manufacturing, Hard Materials and Diamond Tools, Hot Isostatic Pressing, Metal Injection Moulding, New Materials and Applications and PM Structural Parts.

An exhibition will run alongside the technical sessions, providing an opportunity for international suppliers to the PM industry to network with new and existing customers

www.europm2015.com

## MicroNano 316L powder for MicroPIM applications

In the December 2012 issue of *PIM International* (Vol. 6, No. 4, pp 51-52) it was reported that a new method has been developed at the Department of Metallurgy and Materials Science at Hanyang University, Korea, for the manufacture of feedstock for μPIM parts using a micro-nano (75:25 ratio) iron powder mixture and low viscosity binder systems.

This combination of the micro-nano iron powder and the low viscosity wax binder allowed feed-stock with 71% powder loading to be injection moulded at low temperature (70°C) and also low pressure (4 MPa). A highly complex shaped double gear was produced which after sintering at 1250°C showed near full density (97% TD) and fine grained microstructure. The nanopowder addition was found to play an important role in producing the feedstock where thanks to the 'roller bearing effect' of nanopowders acting as a lubricant in mixing, a homogeneous distribution of the nanopowders in the micro powders was achieved.

Now the research group led by Professor Jai-Sung Lee has extended the micro-nano powder combination to 316L stainless steel powders with equally interesting results. According to a paper by J.-P.Choi, *et al* published in *Powder Technology* (Vol. 261, 2014, 201-209), commercial

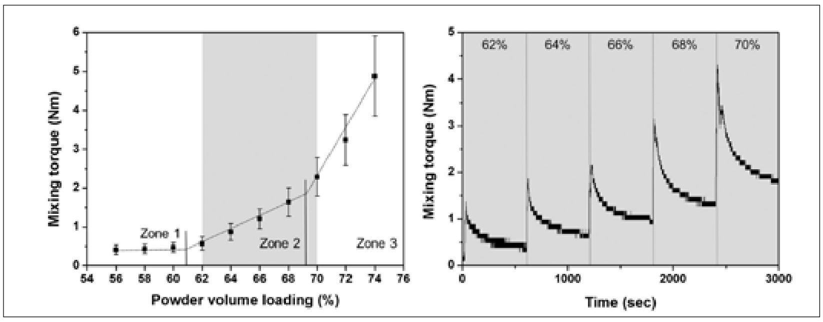


*Fig. 1 Mixing torque variation with continuously increased powder volume loading*

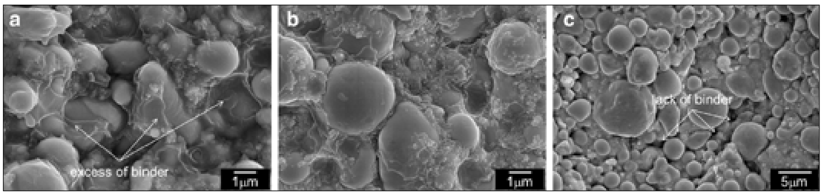


*Fig. 2 Micrographs with powder volume loadings of (a) 60%, (b) 66% and (c) 72%*

water atomised 316L 'micro' stainless steel powders with an average particle size of 4 μm was mixed with 316L nanopowder with an average particle size of 100 nm. The nanopowder was produced by Nano Tech Inc., Korea, using a pulsed wire explosion (PWE) method. As with the micro-nano iron powder mixture previously reported, the composition for the 316L stainless steel mixture was also prepared using the 75 vol% to 25 vol% ratio. However, for this study the researchers simplified the binder system in the feedstock using only paraffin wax as the major component and stearic acid to help the flow of the powders during mixing and injection moulding of the feedstock. Powder loading in the feedstock was tested in the range 56 to 74 vol%, Fig. 1.

During mixing of the feedstock, the 316L nano-agglomerate powders were crushed and rearranged into the interstices of the micro powders. Such particle rearrangement is considered to improve the microstructural homogeneity of the feedstock. SEM micrographs showed that with a powder loading of 60%, which corresponds to zone 1 in Fig. 1, there is a large excess of binder which causes binder-powder separation during injection moulding (Fig. 2a).

The feedstock with the 66 vol% loading showed that the powders are homogeneously covered with the binder and are well dispersed into the feedstock (Fig. 2b) and Fig. 2c shows that there is not enough binder present to cover all of the powder surfaces in the feedstock with 72 vol.% powder loading.

The researchers state that insufficient binder yields, pores, and binder powder separation in the feedstock consequently lead to moulding difficulty. Based on the results from the torque rheometer and microstructure observation, critical and suitable powder loading should be established in the composition range in zone 2 of Fig. 1. However, the authors concluded that feedstock with 66 vol.% powder loading has the best rheological properties, and this is considered as the optimal powder loading for injection moulding.

To investigate the feasibility of the feedstock for injection moulding, the subsequent moulding process was conducted at 70°C at a pressure of 4 MPa to produce a double gear component (Fig. 3). It can be seen that the injection moulded part has a uniform structure without defects or cracks. The measured green density of the 316L micro-nano powder was 65.6± 0.02% of the theoretical density, in good agreement with the powder and binder fraction of the samples.

www.hanyang.ac.kr

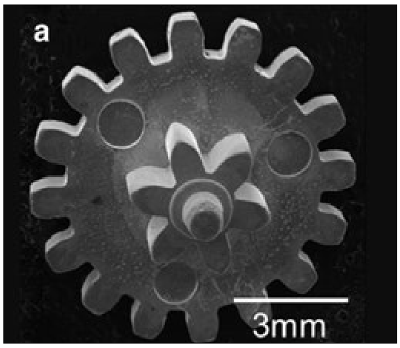


*Fig. 3 The double gear component made using the feedstock with 66 vol.% powder loading*

# Fine spherical iron powders produced by new hydrogen reduction process

Most fine spherical iron powders suitable for Metal Injection Moulding (MIM) are produced either by the carbonyl iron process or by gas atomisation. Both routes produce powders which are relatively expensive, with the cost of powders in the price range of €7 to €10 per kilo. A new process which produces a lower cost fine spherical iron powder was recently announced by the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) in Dresden, Germany, using fine granulated iron oxide from a steelmaking by-product.

Gunnar Walther and his colleagues reported on the new powder producing technology in a presentation at Euro PM2013 in Gothenburg [1], and also in a paper published in the July 2014 issue of *Powder Metallurgy* [2] which gave further details including the sinterability of the new grade and comparisons with carbonyl iron and atomised iron powder.

The technology developed at IFAM Dresden involves a two-step heat treatment/reduction approach to overcome the problems normally associated with reduction of fine iron oxide powder, namely rapid re-oxidation and the pyrophoricity of the reduced powder. The IFAM process first involves milling of the iron oxide powder to achieve mean particle size of <1 µm. The oxide powder was then mixed with a binder, plasticator and dispersant in a ball mill to produce a slurry for spray drying. The resulting spray dried agglomerated granules were sieved to a particle size fraction < 32 µm for the subsequent hydrogen reduction process in a ceramic tube furnace. Hydrogen reduction of the oxide granulate takes place in two stages; the first stage is for one hour at 500°C. At the end of this stage the powder is highly pyrophoric because of its high specific surface. The temperature was then raised in the second stage to between 700°C and 850°C for 24 hours. Fig. 1 shows the steps of the process, and Fig. 2 shows SEM image of the spherical iron oxide after granulation (spray drying).

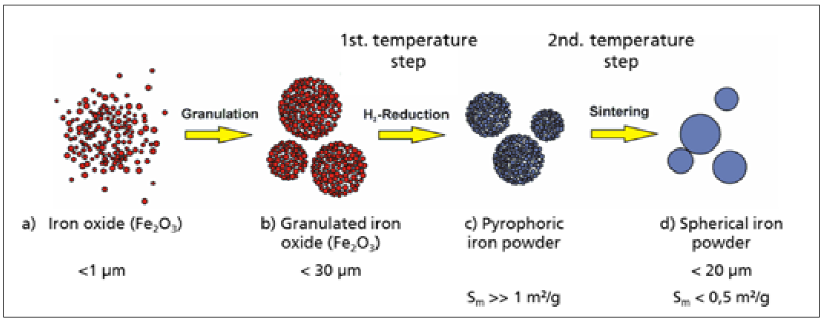


*Fig. 1 Process steps of the new method for manufacturing fine spherical iron powders developed at Fraunhofer IFAM Dresden [1]*

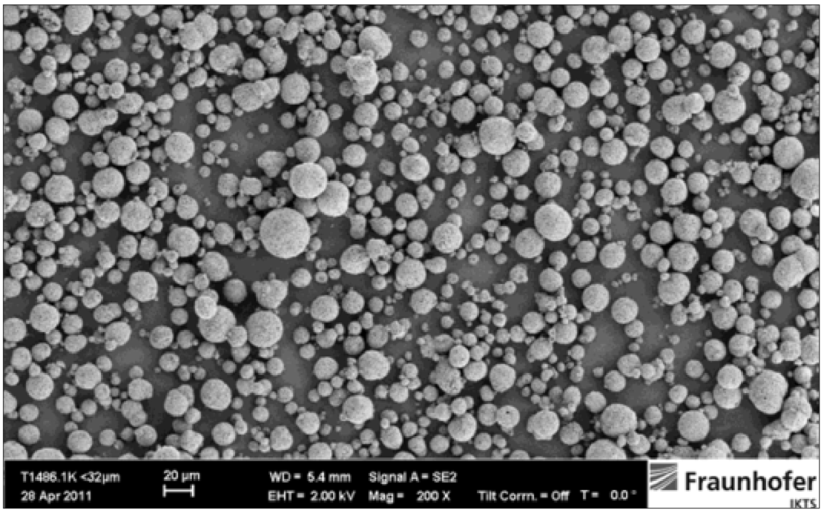


*Fig. 2 SEM image of the spherical iron oxide after granulation (Fraunhofer IFAM) [1]*

It was reported that at 850°C the primary particles within the reduced granulate have sintered to a dense spherical particle whilst the granulate itself was found to only slightly sinter together. Therefore from a starting granulate size of 32 µm a spherical powder size of <20 µm was achievable in the reduced powder through weight reduction.

The next important step is the crushing of the reduced agglomerate using a mortar grinder or hybridizer milling technology to reduce particle size and increase apparent density, but keeping the spherical shape of the powder and preventing particle deformation. Fig. 3 shows a SEM image of iron powder reduced at 500°C for 1 hr + 850°C for 1 hr in hydrogen and milled in a Nara Hybridizer. The best result was achieved when a Nara hybridizer was used to mill the iron powder reduced at 700°C in the second step [2]. A spherical particle shape was obtained and the particle size could be reduced from d50 = 18.6 µm to 5.1 µm. This even smaller particle size was obtained by densifying the still porous iron particle surface and then rounding the resulting particles. The researchers are confident that particle size could be decreased further by optimisation of the milling process and by production of finer iron oxide granules which in turn could considerably enlarge the field of application especially in MIM.

The authors also compared the shrinkage behaviour and sinterability of the new grade of iron powder with atomised spherical iron powders

  

| | Particle size $d_{50}$/µm | Green density g/cm³ | Sintering shrinkage % | Sinter density (geometric) | | Oxygen content % | C content % |
|---|---|---|---|---|---|---|---|
| | | | | g/cm³ | %TD | | |
| Carbonyl-Fe | 4.5 | 4.44 | 15.76 | 7.64 | 97.1 | 0.050 | 0.14 |
| Atomised Fe, spherical | 13.7 | 5.06 | 7.26 | 6.33 | 80.4 | 0.059 | 0.023 |
| Reduced 500°C, 1 h+700°C, 24 h | 18.6 | 3.22 | 25.5 | 7.69 | 97.6 | 0.068 | 0.013 |
| Reduced 500°C, 1 h+850°C, 1 h+ milled 20 min (MG) | 13.8 | 4.57 | 15.3 | 7.33 | 93.2 | 0.091 | 0.036 |
| Reduced 500°C, 1 h+700°C, 24 h+milled 4 min, 16 000 rev min−1 (NH) | 5.1 | 4.67 | 16.0 | 7.75 | 98.4 | 0.161 | 0.015 |
| Reduced 500°C, 1 h+850°C, 1 h+ milled 120 min, 100 rev min−1 (BM) | 12.3 | 4.06 | 18.4 | 7.47 | 94.9 | 0.066 | 0.021 |

*Table 1 Comparison of sintering behaviour of reduced and milled powders with commercial carbonyl and atomised spherical iron powders: MG, grinding mill; PBM, planetary ball mill; NH, Nara Hybridizer [2]*

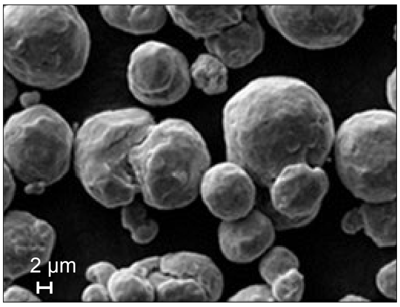


*Fig. 3 SEM image of powder reduced at 500°C for 1 h + 850°C for 1 h under hydrogen and milled for 4 min, 16 000 rev min−1 in a Nara Hybridizer [2]*

and carbonyl iron [2]. As can be seen in the table the shrinkage of 16% of the powder milled in the Nara Hybridizer is comparable with that of the carbonyl iron powder compact, whereas the unmilled powder has a shrinkage of over 25% because it has not been densified by the milling process. Samples for sintering had been prepared by compacting a mixture of 0.5 wt-% binder (PVP) in a press under a pressure of 100 MPa, which correlates with the injection pressure for a MIM process. The samples were sintered at 1320°C for 3 h under hydrogen in a tube furnace. The as sintered sample density, the porosity (by image analysis of metallographic sections) and the shrinkage (by measurement of the dimensions before and after sintering) were determined, as shown in Table 1.

### References

[1] 'New Method for Producing Fine Spherical iron Powders' by G. Walther, T. Buttner, B. Kieback, T. Weissgaerber (Fraunhofer IFAM Dresden), and M. Hoffmann, T. Blum (Ostec Gmbh), presented at Euro PM2013 Congress, Gothenburg, Sweden, and published in the Proceedings by the European Powder Metallurgy Association, Shrewsbury.

[2] 'Properties and Sintering Behaviour of fine Spherical Iron Powders Produced by a new Hydrogen Reduction Process', by G. Walther, T. Buttner, B. Kieback, T. Weissgaerber (Fraunhofer IFAM Dresden), and M. Hoffmann,, G. Bachmann (Ostec GmbH). *Powder Metallurgy* Vol. 57, No. 3, July 2014, 176-183

# Powder Metallurgy day announced at Ceramitec 2015

Ceramitec 2015, the international trade show covering the technical ceramics and Powder Metallurgy industry, will take place in Munich, Germany, October 20–23, 2015.

A Powder Metallurgy Day is scheduled for the afternoon of the first day, Tuesday October 20. This will be followed by the Heavy Clay Day on Wednesday and the Technical Ceramics Day on Thursday.

In 2015 Ceramitec will see a further enlargement of the 'Technical Ceramics' and 'Powder Metallurgy' areas, as well as maintaining a focus on its conventional segments of raw materials, heavy clay ceramics, fine ceramics and refractory ceramics.

As in previous shows, the Ceramitec 2015 exhibition will be accompanied by a supporting programme of technical presentations. The Ceramitec Forum will once again serve as a platform for the transfer of knowledge and know-how, for research and development. Attendance at the specialist lectures and panel discussions will be free of charge. The lectures are offered with simultaneous translation in German and English.

Inovar Communications will be exhibiting at Ceramitec 2015 and copies of *Powder Metallurgy Review* (Autumn/Fall issue) and *PIM International* (September issue) will be distributed from the entrance to the PM and Technical Ceramics hall. For advertising information please contact Jon Craxford, Advertising Sales Director, Email jon@inovar-communications.com

www.ceramitec.de

## MIM 2015 Tampa: Conference Programme now available

The MIM2015 International Conference on the Injection Molding of Metals, Ceramics & Carbides will be held at the Sheraton Tampa Riverwalk Hotel, Tampa, Florida, USA from February 23-25 2015. The conference, which is sponsored by the Metal Injection Molding Association (MIMA), has the objective of exploring the latest advances in MIM, assisting in the transfer of technology, and investigating new developments in the field of injection moulding of metal, ceramics, and carbides.

In addition to regional review presentations and technical presentations, a number of PIM design case studies will be featured throughout the conference. There will also be a workshop on Energy Management in MIM Processing by Robin Kent, Tangram Technology, USA, on the afternoon of Wednesday February 25. This workshop covers all aspects of energy management for MIM, including processing methods, operations, monitoring and targeting.

Immediately prior to the conference, on February 23, a one day PIM tutorial will be conducted by Prof Randall German, San Diego State University. This optional course, which requires a separate registration fee, is an ideal way for anyone looking for a solid grounding in PIM to obtain a comprehensive foundation in a short period of time.

www.mpif.org

*The Sheraton Tampa Riverwalk Hotel*

## PM property database celebrates ten years

The online Global PM Property Database (GPMD), which welcomed its first users in October 2004, has over the last ten years become an important resource for designers and engineers around the world. The database, which is available free of charge to registered users, is a project funded jointly by North America's Metal Powder Industries Federation (MPIF), the European PM Association (EPMA), and the Japan PM Association (JPMA).

Originally covering only the ferrous PM industry, the website has since been refined and extended to include the nonferrous PM and MIM sectors and now contains nearly 4,000 lines of high-quality data. The data is fully searchable and outputs can be exported to several well-known FEA packages.

www.pmdatabase.com


→ 31 August
– 3 September 2015
in Lüneburg / Germany

HELMHOLTZ-ZENTRUM GEESTHACHT

The Helmholtz-Zentrum Geesthacht,
Center for Materials and Coastal Research
invites you to

# Congress
# PM Titanium 2015

From **31 August to 3 September 2015** the

## 3rd Conference on Powder Processing, Consolidation and Metallurgy of Titanium

will take place at the Leuphana University in Lüneburg, near Hamburg, Germany.

Following the very successful conferences in Brisbane/AUS (2011) and Hamilton/NZ (2013) experts on powder metallurgical processing of titanium and titanium alloys will meet again for discussing status and progress on relevant PM titanium topics.

Further information and a Call for Papers:

**www.hzg.de/pmti2015**


Lüneburg is an ancient city from the Middle Ages close to Hamburg with picturesque houses, small streets and a lot of cosy cafés and pubs. Thus, it provides an optimal ambience for fruitful networking activities around the presentations.

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## Degradable PIM implants promise fewer surgeries

Until now, in cases of bone fracture, doctors have used implants made of steel and titanium, which have to be removed after healing. To spare patients further interventions, researchers at the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) in Bremen, Germany, are working on a bone substitute that completely degrades in the body. Towards this end, material combinations of metal and ceramic are being used.

No other joint in the human body is as highly mobile as is the shoulder. It is, however, also very sensitive and prone to injury, with athletes being particularly affected. The most common complaints include tendon rupture, which has to be treated surgically. The surgeon fastens the cracks using suture anchors. Such implants used to be made of titanium or non-degradable polymers, with the disadvantages that either they remain in the body even after healing has occurred or doctors have to remove them in a second procedure. To avoid this researchers have developed load bearing, biodegradable implants that are completely degraded in the body. In the first step they used Powder Injection Moulding (PIM) to manufacture a suture anchor which is available as a demonstrator.

*A suture anchor made of iron-tricalcium phosphate (FE-TCP). Photo © Fraunhofer IFAM*

"With the implant, severed tendons can be anchored to the bone until they have grown again. Since the function of the fixing element is satisfied after the healing process, it is no longer needed in the body. If implants or protheses that are as wear resistant as possible are required, such as in an artificial hip joint, metallic alloys such as titanium will certainly continue to be used. However, for plates, screws, pins and nails which should not remain in the body, there are other requirements," stated Dr Philipp Imgrund, Manager of the Medical Technology and Life Sciences area at IFAM.

In a project called DegraLast, IFAM has worked jointly with the Fraunhofer Institutes for Laser Technology (ILT), for Biomedical Engineering (IBMT) and for Interfacial Engineering and Biotechnology (IGB) in establishing a materials and technology platform to produce degradable bone implants for use in trauma surgery and orthopaedics. These materials are to be gradually absorbed by the body while, at the same time, new bone tissue is formed. Ideally, the degree of degradation is adapted to the bone growth so that the degradation of the implant meshes with the bone formation. For this reason, the scientists are developing materials with specifically adjustable degradation.

The challenge is that the implants have to be mechanically stable enough during the entire healing process so that they are able to fix the bone in place. At the same time, they cannot have any allergenic effects or cause inflammation. The researchers at IFAM are relying on metal-ceramic composites, with a metal component based on an iron alloy being combined with beta-tricalcium phosphate (TCP) as the ceramic component. "Iron alloys corrode slowly and ensure high mechanical strength, while ceramic decomposes quickly, stimulates bone growth and aids the ingrowth of the implant," Imgrund explained. In laboratory experiments the researchers found the optimum composition of the materials for the suture anchor. The demonstrator consists of 60% iron and 40% ceramic. They succeeded in doubling the degradation rate from 120 to 240 µm per year in the laboratory model. The shoulder anchor would be absorbed by the body within one to two years.

www.ifam.fraunhofer.de

# Metal Injection Moulding in the firearms industry: A global perspective

The firearms industry is a major consumer of Metal Injection Moulded (MIM) parts, accounting for significant levels of production not only in North America, but also Europe and Asia. As an industry that encompasses both civilian, law enforcement and military markets it is a sector that is subject not only to consumer trends, but to national and international political events. In this article Nick Williams, Editor of *PIM International*, reviews trends in the use of MIM components in firearms, looks at regional variations and considers opportunities for the future.

Metal Injection Moulding's ability to provide high volumes of net shape components at competitive prices from a wide range of alloys to very tight tolerances, whilst at the same time offering excellent mechanical and corrosion resistance properties, has played an important role in transforming the way firearms companies are now able to design and manufacture components.

Whilst most attention has traditionally been given to the use of Metal Injection Moulding in the North American firearms industry, the use of MIM technology in this sector is truly global and it is estimated that firearm components could account for at least 7% of MIM's global annual sales of approximately $1.5 billion.

The methods by which firearms are manufactured has changed dramatically over recent decades. In the days of forged and machined parts firearms would be manufactured by fitters, with components honed and adjusted as necessary to make them function as required. This labour intensive process was inevitably time consuming and accounted for a significant part of total manufacturing costs. Advanced manufacturing techniques such as MIM offer complex parts with such exceptional tolerances and repeatability that guns can today be assembled with much less of a requirement for hand-fitting, thereby dramatically reducing manufacturing time and costs.

The primary advantage of MIM's net shape capability is the elimination, or significant reduction, of machining operations in the high-volume production of complex shaped components. It has been suggested that this can save up to 40% on machined or investment cast equivalents. A trend towards more compact firearm designs with smaller, more intricate parts also plays to MIM's advantages of high part complexity and thinner walled sections. The ability to include

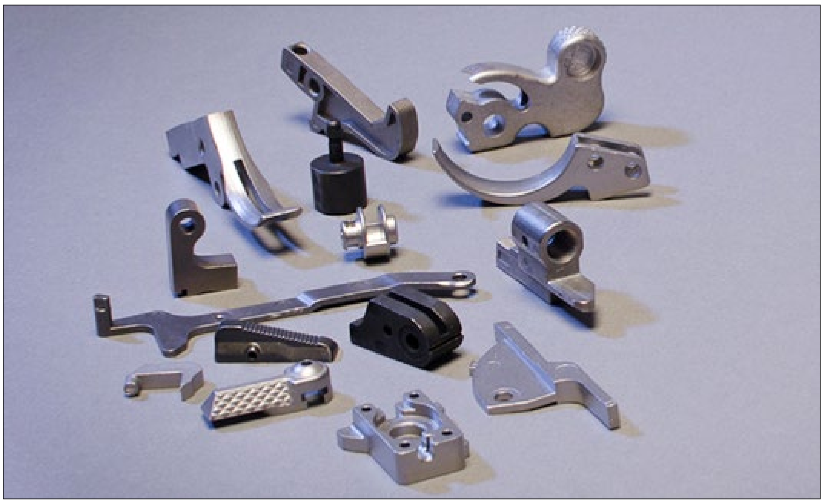

*Fig. 1 A selection of MIM firearms parts manufactured by Netshape Technologies, Inc.*

*Fig. 2 Injection moulding of MIM parts at Advanced Forming Technology (AFT), an ARCMIM company, in Longmont, Colorado, USA*

*Fig. 3 MIM firearms parts entering a continuous pusher sintering furnace at Megamet Solid Metals Inc, St. Louis, USA*

logos and lettering is another benefit that is far more costly to perform with other technologies.

Almost all major firearm manufacturers around the world have already adopted MIM, and some of those who have not yet adopted the technology are now scrambling to catch up. What is clear is that when new firearms projects are planned by manufacturers, MIM parts are high on the wish list due to their competitive cost and the consistency of the MIM process.

Parmatech Corporation, the company that first developed and pioneered the MIM process in the US in the late 1970s, has witnessed first-hand the adoption of MIM technology by the firearms industry. Dan (DJ) Lauck, Parmatech's Sales Manager, told *PIM International*, "There were early adopters in the market that now have decades of experience using MIM components. More and more companies have seen this sustained use of MIM components and are now starting to adopt this technology as well, primarily to reduce cost on existing products. The hesitation, if any, from prospective users in using this technology is more to do with fears around reducing the utilisation of their installed manufacturing base. Why buy outside MIM parts and let our internal machining lines die? I've even been told 'when that 50 year old forging press finally breaks and can't be fixed, we'll start looking into MIM to make the parts.'"

A wide range of parts are today manufactured by MIM for both military and civilian applications including hammers, triggers, trigger guards, sights, gun bodies, safety switches, sears, extractors, bolts, magazine catches, levers, selectors, grips and carrying handles.

There is no doubt that firearms manufacturers appreciate the advantages that MIM offers. In a report published in *PIM International* in 2012, John Lewinski, Director of Supplier Management at Smith & Wesson, stated that, "MIM has allowed us to take cost out of the product while maintaining quality and therefore pass the savings on to the consumer" [1]. Kevin Collins, a Senior Design Engineer at Savage Arms in Westfield, MA, USA, cited MIM as "the modern replacement to investment casting, especially for small parts," adding that MIM firearm parts are dimensionally consistent, fairly inexpensive and the surface finish is smoother than machined or investment cast components [1].

## An introduction to the MIM process

The primary raw materials for MIM are fine metal powders and a thermoplastic binder. The binder is only an intermediate processing aid and is removed from the products after injection moulding. Binders are designed to be removed in two stages, with the first stage binder normally a wax or polyacetal and the second stage binder typically a polyethylene or polypropylene. The properties of the powder determine the final properties of the MIM product. The blended powder mix is worked into the plastified binder at powder/binder ratio typically around 60:40 using a kneader or shear roll extruder at an elevated temperature. The inter-mediate product is the so-called feed-stock. It is usually granulated with granule sizes of several millimetres, as is common in the plastic injection moulding industry. Feedstock can either be purchased 'ready to mould' from a range of international suppliers, or it can be manufactured in-house by a MIM producer if the necessary skills and knowledge are available. Parts are formed in an injection moulding process similar to plastic injection moulding, with a few equipment component changes to accommodate extra material and the need for different pressures and temperatures. These parts, with the thermoplastic binder still in place, are referred to as 'green' parts.

The subsequent binder removal processes serve to obtain parts with an interconnected pore network without destroying the shape of the component. At the end of the first stage of the binder removal process the second stage binder remains in place, holding the metal powder particles together. At this stage, the parts are referred to as 'brown' parts. The pore network that has been created allows evaporation of the second stage binder quickly during the thermal debinding phase prior to sintering, at the same time as sintering necks start to grow between the metallic particles.

The parts are then sintered, a process of interparticle atomic diffusion that leads to the elimination of most of the pore volume formerly occupied by the binder. As a consequence, MIM parts exhibit a substantial shrinkage during sintering. The linear shrinkage is usually as high as 18 to 22%, and this is accommodated by the uniform oversizing of injection moulded tools. If required, sintered MIM parts may be further processed by conventional metalworking processes like heat treatments or surface treatments in the same way as cast or wrought parts.

*Fig. 4 This MIM titanium trigger is shown in the green and sintered state and was manufactured by Mimest SpA, Trento, Italy*

*Fig. 5 This 2014 MPIF award winning MIM part was manufactured by Advanced Forming Technology, an ARCMIM Company, and is used in a lock hood for a Smith and Wesson muzzleloading rifle. Manufactured via MIM from 4605 low-alloy steel, the hood's complex geometry presents a challenge in maintaining the large U-shape sufficiently undistorted so that it can be coined into final tolerance. This is accomplished using an 'active' setter made of a feedstock having a similar shrink rate to the hood (Photo courtesy MPIF)*

## MIM material grades used in the firearms industry

Materials commonly used in MIM firearms components include low alloy steels and stainless steels. However more exotic materials such as titanium, more commonly used in advanced MIM applications in the aerospace and medical industries, have also been processed by MIM for firearms applications (Fig. 4).

Georg Breitenmoser, Managing Director of Swiss MIM manufacturer Parmaco Metal Injection Molding AG, told *PIM International*, "In principle all the materials which the firearms industry requires are available to be processed by MIM. Of course sometimes there isn't an exact match between standard specifications and the MIM material. In this instance we need some flexibility on the customer's side. MIM materials have usually somewhat lower strength and lower ductility than wrought grades of the same composition; however the difference is usually small enough to allow use of the MIM equivalent of the wrought grade. If there is the need for a new material it's not powder availability which is the problem - there are powder suppliers who make any grades in any quantities. It is rather the availability of feedstock and

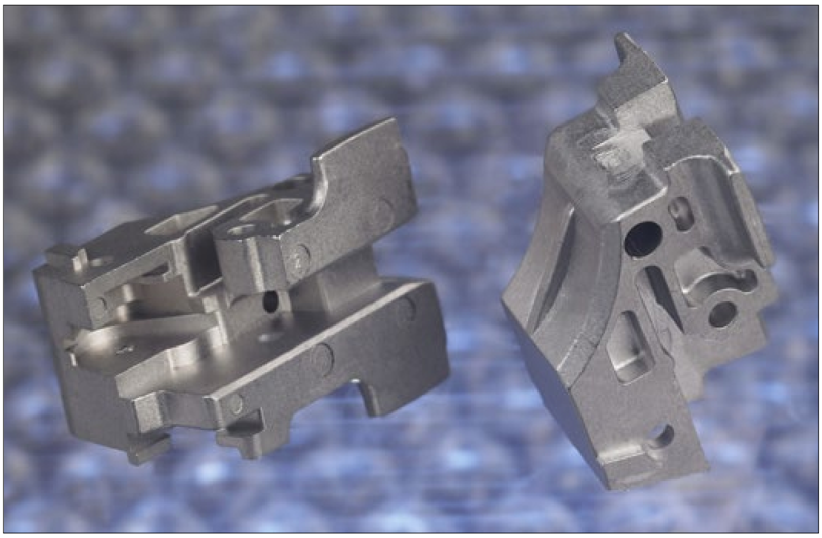

*Fig. 6 A 2009 MPIF award winning handgun housing block manufactured by Parmatech Corporation, Petaluma, California, USA. This 420 MIM stainless part is used in a 45-calibre handgun and contains the firearm's spring mechanism and provides sliding action with other mechanical parts. This complex MIM part features wings, undercuts, through-holes and blind holes, as well as thin and thick cross sections (Photo courtesy MPIF)*

the availability of the accompanying processing information which can hold those MIM companies back who do not produce their own feedstock."

Parmatech's DJ Lauck commented, "420 stainless steel appears to be the alloy of choice for many of the firearms components. Complex components in polymer pistols are also increasing in the industry. When we introduced our MIM-420 and MIM-4140 alloys in 2003, we saw immediate use of these materials away from the MIM-2700 and MIM-17-4 alloys."

Manuel Caballero, Technical Director at leading European MIM producer Mimecrisa SA, Spain, told *PIM International*, "Most of our Metal Injection Moulded parts are produced using fully hardened low alloyed steels MIM-4140 and MIM-8740, or a case hardened steel such as MIM-8620, as well as 17-4PH stainless steel. Iron-nickel materials are also suitable for many firearms applications." Typical material properties of heat treated MIM-4140, as published in *MPIF Standard 35, Materials Standards for Metal Injection Molded Parts*, are shown in Table 1.

One current drawback with MIM technology is material designation and selection, as many engineers are not familiar with the materials used for MIM parts. Kevin Collins, a Senior Design Engineer at Savage Arms, USA, stated that, "Most MIM parts are not made from common AISI materials such as 4340 and 8620 alloy steels, and this is certainly a drawback for anyone wanting to make parts for existing military rifles such as the M14 and M16" [1].

Data for a range of MIM and PM alloys are available in the online Global Powder Metallurgy Property Dababase (www.pmdatabase.com). The database is the result of a global collaboration between the three major regional trade associations, the European Powder Metallurgy Association (EPMA) North America's Metal Powder Industries Federation (MPIF) and the Japan Powder Metallurgy Association (JPMA).

## North America

The North American firearms industry was one of the first adopters of Metal Injection Moulding as a production process. Ray Millett, one of the inventors of the MIM process at Parmatech, established Millett Sights in 1981 to produce MIM gun sights and mounting systems and as such can be credited as the first producer of MIM firearms parts. Many firearms manufacturers have since established in-house MIM operations with America's oldest gun maker, Remington Arms, being one of the earliest, starting in-house MIM production in 1984.

There are currently around 70 companies manufacturing MIM parts in North America, of which an

| | Tensile Properties | | | Elastic Constants | | | Hardness | |
|---|---|---|---|---|---|---|---|---|
| Density | Ultimate Strength | Yield Strength (0.2%) | Elongation (in 25.0 mm) | Young's Modulus | Poisson's Ratio | Unnotched Charpy Impact Energy (A) | Macro (apparent) | Micro-indentation (converted) |
| g/cm³ | MPa | MPa | % | GPa | | J | Rockwell | |
| 7.5 | 1,650 | 1,240 | 5 | 205 | 0.28 | 75 | 46 HRC | N/D |

*Table 1 Material properties (typical values) for quenched and tempered MIM-4140, as published in MPIF Standard 35, Materials Standards for Metal Injection Molded Parts. NOTES: (A) Impact energy values derived from an un-notched 5 mm x 10 mm cross-section Charpy specimen (see MPIF Standard 59), N/D Not determined for the purposes of this standard*

estimated 25%, or 18 companies, are captive operations. The total North American MIM market (all sectors) is estimated to be worth \$300-350 million, with the sizes of operations ranging from fewer than 20 employees to more than 300. Current annual growth estimates recently reported by members of the US-based Metal Injection Molding Association (MIMA), and association of the Metal Powder Industries Federation (MPIF) are in the region of 15-20% per year.

Today the firearms industry in North America is the single largest consumer of MIM components, with figures estimating that more than 40% of MIM components by weight produced in the region are for firearms applications. In terms of sales value, MIM components for the firearms industry are said to have the largest market share at 25%, followed by medical devices and dental applications at 23%, and automotive at 12%.

*Fig. 7 AR-15 rifle parts manufactured by Megamet Solid Metals, Inc.*

**Understanding the boom in US firearms sales**

The boom in firearms sales in the US in recent years resulted in some challenging years for MIM suppliers, who struggled to keep up with the ever increasing demand for components. The November 2008 election of Barack Obama to the presidency of the USA is widely recognised as the initial driver for the run on firearms sales in the US, with many users and enthusiasts fearing that some form of legislation would

*Fig. 8 This 2010 MPIF award winning 17-4 PH stainless steel MIM upswept grip safety was manufactured by Megamet Solid Metals, Inc. and is used in a 1911 45-calibre pistol made by Colt's Manufacturing Company, LLC. The upswept design of the grip safety part, which was traditionally investment cast, would previously require extensive secondary machining. Switching to MIM reduced lead times and provided exceptional cost savings, in addition to increasing production rates and producing a more uniform part. Colt performed a 10,000 cycle test to qualify the part (Photo courtesy MPIF)*

*Fig. 9 This 2009 MPIF award winning MIM handle body and yoke was manufactured by Megamet Solid Metals for Colt Canada Corporation. Made from 4140 low-alloy steel, the parts are core components in a folding-front-grip assembly used on modern military rifles. Post-sintering operations included coining, reaming, and tapping. The components are quenched and tempered to a 45-50 Rockwell C hardness range. Parts are supplied to the customer with a manganese phosphate finish (Photo courtesy MPIF)*

be passed restricting ownership.

The unprecedented demand for MIM components for firearms continued after the 2012 re-election of Obama and placed extreme pressure on the capacity of many MIM producers who supplied this sector. The nature and speed of the MIM process, however, gave the industry a competitive advantage over competing technologies. As Parmatech's DJ Lauck stated, "Production volume flexibility with the MIM process allowed more rapid reactions to market fluctuations and increased production demands without adding more milling machines."

Only recently have there been signs that the US firearms industry has started to normalise. Kevin Schwindt, Vice President Sales & Marketing at ARCMIM, told *PIM International*, "The US markets have normalised to more regular run rates for our customers, but people continue to purchase firearms. We are seeing more interest globally for more MIM products within the firearms industry." Schwindt stated, however, that a normalisation in the firearms industry by no means indicates a market crash. "The firearms industry is a very large, very strong industry both in the US and globally. The last three years have been unprecedented concerning the number of guns sold and that has finally slowed down. This does not mean that the industry, and how MIM supports it, will dramatically decrease. Like any other industry, we have challenges and demand goes up and down, so we must continue to push forward and learn how to help our customers be more competitive in order for them to continue to sell firearms."

**'Increasing adoption of MIM technology from various firearms manufacturers is sustaining overall growth, and the early adopters continue to put more MIM components in their new product offerings'**

DJ Lauck commented, "I would say the firearms market is still a growth market for MIM companies. Increasing adoption of MIM technology from various firearms manufacturers is sustaining overall growth, and the early adopters continue to put more MIM components in their new product offerings."

Parmatech's President Rob Hall echoes this sentiment, in which growth for the MIM industry is anticipated in the form of new applications rather than volume increases of existing components. Hall told *PIM International*, "We see the current status as strong

  

*Fig. 10 This 2013 MPIF award winning U-bracket and stop is manufactured by Polymer Technologies and used in a Feedbox Support Improvement Kit (FSIK) for an M249 squad automatic weapon (SAW). The innovative I-beam and webbing design allowed the parts to meet the 32–38 HRC hardness range requirement whilst also saving on weight. Moulded from MIM-17-4 PH stainless steel, the parts have >7.5 g/cm³ density, 130,000 psi ultimate tensile strength, 106,000 psi yield strength, and 6% elongation (Photo courtesy MPIF)*

for MIM components. Many OEMs have transitioned from 'converting machined parts to MIM' to 'designing for MIM' and are realising the substantial benefits of the MIM process."

Within the US firearms industry, Bruce Dionne, Vice President - General Manager at Megamet Solid Metals, Inc. also believes that there are still significant growth opportunities for MIM. "We have helped companies that have never used MIM to adopt the process, dramatically increasing their success and profitability and securing them as loyal and committed customers. There are still huge opportunities for MIM in this sector, especially amongst the aftermarket producers where there simply isn't the understanding of what MIM can offer them in terms of innovation and profitability."

In the US, domestic MIM manufacturers have a significant advantage over international suppliers of firearms because of the International Traffic in Arms Regulations (ITAR) regulations. ITAR covers the control and distribution of technical data for defence related articles, from firearms to space vehicles. The control and availability of technical data covered under ITAR carried with it certain requirements, including restrictions on the sharing of this data, including technical drawings for certain MIM firearms parts.

Parmatech's DJ Lauck commented, "Regulatory requirements for firearms continue to be rolled down the supply chain. It took some period of time for ITAR regulations to be fully understood by the industry, and there is significantly more understanding of these requirements than was in place just seven years ago."

**Combatting negative associations within the US gun community**

Unlike other consumer sectors gun enthusiasts, particularly in the US, are more likely to strip down their guns, make close inspection of components, and even perform modifications and adjustments, in other words try and perform traditional gunsmithing tasks. The appearance of components manufactured using a very different process, using different materials and exhibiting different properties inevitably brought some negative comparisons. This fear of the unknown, combined with a small number of sub-standard parts that were widely reported within the gun community, led to the establishment of a 'No-MIM' campaign amongst enthusiasts, perpetuating a number of misunderstandings about the process and its capabilities.

Some conventional component producers saw the opportunity to manufacture aftermarket replacement parts that were guaranteed not to be manufactured by MIM, whilst a number of smaller gun companies who were not using MIM also saw a marketing opportunity. Opposition to MIM appears, however, to have subsided as major manufacturers came out in defence of the process and its benefits to the industry.

Bruce Dionne, commenting in his capacity as President of the Metal Injection Moulding Association (MIMA) told *PIM International*, "Negative reactions to MIM have existed from the beginning, especially with those that do not understand the technology or do not wish to understand the technology. Early on in the firearms industry there were MIM providers that oversold the technology's capabilities and some part failures brought a negative reaction to the technology. This has been easy fodder for companies that machine all of their parts, touting that MIM is inferior. The truth is that every manufacturing solution brings with it pros and cons. While MIM does have slightly different properties than wrought materials, the cost benefits have significantly outweighed any minor material trade-offs."

Dionne continued, "The answer has been, and continues to be, education. When designers and users are educated on, and plan for, the design requirements of MIM, these projects have proven to be extremely successful. If this were not the case, you would not see all major manufac-

*Fig. 11 A MIM underbarrel manufactured by Mimecrisa, Spain, from 8740 heat treatable steel and hardened to 33-37 HRC. The part weighs 168 g and one of the main processing challenges was achieving a flatness of 0.15 mm*

*Fig. 12 A MIM Fe8Ni double hammer manufactured by Mimecrisa, Spain*

turers adopting MIM as one of the premier manufacturing processes for all of the small metal parts used in their designs. Any fear that still exists that MIM parts are not viable in the firearms industry is being proliferated by suppliers and manufacturers that are too small to benefit from the tooling investment or that have carved out a niche selling to the misinformed."

Kevin Schwindt stated, "Any change in a process causes concerns and the MIM industry is no different. I think the data and the long history of minimal issues that reach the end customers have proven to be the best way to address any negative reactions."

DJ Lauck stated, "MIM has benefited the firearms industry primarily by allowing higher volume production with limited footprint increases. The sustained successful use of MIM components by leading firearms manufacturers shows the technology itself is qualified to be used. This does not discount past errors in the application of the MIM technology, and also quality problems exhibited by some MIM producers in the past have led to some of this perception."

## South America

The firearms industry in South America is dominated by Brazil's Forjas Taurus. Forjas Taurus, headquartered in Porto Alegre-RS, is a publicly traded Brazilian engineering corporation. As well as being the largest producer of handguns in Latin America, and one of the largest in the world, the business is composed of seven units in Brazil and two in the USA with production facilities that manufacture weapons, parts, helmets for motorcyclists, ballistic vests, injected plastic products, hand tools and machine tools.

Forjas Taurus has a major captive MIM operation and the acquisition of Steelinject Injeção de Aços Ltda from the Lupatech Group at the end of 2011 gave the company additional capacity as well as the choice of two feedstock systems for the manufacture of MIM parts for internal use and for a growing international customer base [2].

Forjas Taurus merged its two MIM operations onto a site in São Leopoldo, Rio Grande do Sul, in 2013. Forjas Taurus' original captive MIM operation uses BASF's Catamold system, whilst Steelinject's technology is based on wax-polymer technology and solvent debinding system originally licensed from Parmatech Corporation.

*Fig. 13 Various MIM firearms parts manufactured by China's Easea International Limited, as featured on www.easeamim.com*

## Europe

The importance of the firearms sector to the European MIM industry has never been particularly clear as MIM industry statistics bundle the firearms industry within generic market areas such as 'General Engineering.' Europe is however an important player within this sector. A number of companies talk openly about their supply of components for civilian and military firearms applications, whilst others are more cautious about operating within this market for commercial or ideological reasons.

It is estimated that there are more than fifty MIM parts producers operating in Europe. However, it is uncertain what percentage of these serve the firearms industry. In addition to commercial MIM parts producers, there are at least three firearms manufacturers with in-house MIM operations in Europe, including Glock in Austria [3], HS Produkts in Croatia and Kalashnikov Concern in Russia [4]. HS Produkts is closely connected with Springfield Armoury Inc., the sole distributor of its firearms in the US - the market that consumes 95% of its products.

Georg Breitenmoser, Managing Director of Swiss MIM manufacturer Parmaco Metal Injection Molding AG, told *PIM International*, "MIM is today well accepted in the European firearms industry. Major producers of firearms cannot forego the cost advantages that MIM offers. Low volume producers are more reluctant to use MIM because the cost advantage of MIM is less relevant or sometimes non-existent."

Comparing the differences in approach between European and North American MIM suppliers, Breitenmoser commented, "I don't think there is much of a difference, although there is a bigger percentage of MIM companies in Europe which are reluctant or unwilling to make firearms parts whereas in the US making firearms parts is not seen as objectionable."

Those who do serve the European firearms industry note that there are a number of challenges ahead. Breitenmoser stated, "The defence industry is dependent on government regulations in many European countries. The regulations are such that it is not allowed to deliver into war zones, or sometimes even into the vicinity of such zones. Although the demand for defence goods seems to be growing, it is uncertain whether the European defence industry can participate due to the aforementioned circumstances."

Mimecrisa, based in Santander, Spain, is one of the top three MIM producers in Europe and an important manufacturer of MIM firearms components. The company's Managing Director, Alejandro Martinez, told *PIM International*, "Growth in recent years has been very high, at over 10% a year. Nevertheless since the second quarter of 2014 the restrictions to export to the Russian market, new regulations for export licences in some EU countries, and overbooking in warehouses in the EU have led to the market falling very quickly. This fall is expected to stop in the next few months or next year."

**Russia**

The use of MIM firearms components in Russia is expected to grow dramatically in the coming years following the announcement in early 2014 that Kalashnikov Concern, part of the Russian state corporation Rostec, was purchasing 51% of the shares in Sintez (Synthesis PD). The cost of the deal, stated Rostec, is more than RUR 250 million (US$ 7.1 million) and is reported to be financed from Kalashnikov's own capital.

Kalashnikov Concern's CEO Aleksey Krivoruchko commented at the time of the announcement, "Partnering with Synthesis-PD is an important step in the modernisation of the entire enterprise's production. Currently, 90% of parts are produced and refined manually, using old technologies that require significant time and effort. Thanks to the experience of Synthesis-PD, we will be able to cut the time required to manufacture parts in half and reduce production costs by more than 40%, as well as improve quality and increase production rates" [4].

This acquisition is just one part of a modernisation strategy incorporating new technology that is designed to reduce costs and increase profits at Kalashnikov. Almost RUR 5 billion ($126 million) is to be invested in modernising the Kalashnikov Concern by 2017, according to Rostec's Sergei Chemezov. Kalashnikov has already launched a modernisation program at its factory in Izhevsk, Udmurtia, 750 miles east of Moscow [5]. The investments will enable the tripling of Kalashnikov's small arms production to around 1.9 million guns per year. The company anticipates more than RUR 9 billion ($226.7 million) in revenue in 2014, compared to over RUR 2 billion ($50.4 million) in 2013. The Russian Industry and Trade Ministry's strategy for the small arms industry until 2020, jointly drafted with Rostec, anticipates that total revenue from small arms sales will reach RUR 24 billion ($604.6 million) over the next six years.

Kalashnikov, which has lost key international civilian sales with the recent imposition of sanctions by the United States and the European Union, has stated that it will increase its focus on the Asian, African, and Latin American markets.

Key decisions on the next generation of Russian military rifles are also expected to be announced in the near future and promise further opportunities for an expansion of the use of MIM technology in the country.

## Asia

### China

China's MIM industry has grown dramatically in recent years, from sales of around $60 million in 2006 to an estimated $230 million in 2012. Whilst the largest MIM producers serve the consumer electronics sector, the firearms industry is served by medium sized Chinese MIM producers [6]. One of the first MIM operations in China, Shandong Jinzhu Material Technology Co., Ltd. (formerly Shandong Jinzhu Powder Injection Molding Co., Ltd.) was founded in 1996 with a focus on MIM firearms components. Examples of MIM components used in firearms manufactured by Norinco, one of China's largest defence technology and engineering firms, can be seen on the firm's CQ-A rifle and include the receiver, trigger guard, magazine release button and carrying handle [7]. MIM firearms parts manufactured by China's Easea International Ltd can be seen in Fig. 13.

### India

Firearms production in India is restricted to Government owned factories belonging to the Ordnance Factory Board. Small arms of the type that use MIM parts are made in three of the 39 factories within this group. It is understood that there is some use of MIM parts with the Ordnance Factory Board and there has been an expression of interest in acquiring a turnkey MIM plant.

Indo-US MIM Tec PVT, based in Bangalore, is one of the world's largest MIM producers and a significant supplier to the international firearms industry. The company states that it currently serves over twenty firearms customers in the US and Europe and has more than 175 critical firearm components in production.

Whilst India itself is not believed to be a significant market for producers of MIM firearms components, the country is being eyed by international firearms manufacturers as a promising potential market. In

February this year Kalashnikov Concern announced that it was considering a joint venture in India with a new plant capable of manufacturing 50,000 weapons per year. It was suggested that any venture would involve the production of combat weaponry as well as firearms for civilian use. "India is a very promising market, and the best way to enter it is to set up production there," stated Alexei Krivoruchko, Chief Executive and part-owner of Kalashnikov Concern, in February 2014. "We will begin to set up production this year." [8]

**Other Asian countries**

Japan, an early adopter of MIM technology, is understood not to have any significant MIM firearms production, with its key markets being automotive, medical devices and industrial equipment. Likewise, there is understood to be little MIM firearms production in Singapore or Taiwan.

## HIP in the manufacture of MIM firearms components

In a drive to deliver parts with the greatest possible performance, 50-60% of all firearms parts manufactured in North America today are Hot Isostatically Pressed (HIPed) to full density in order to improve toughness, ductility and fatigue strength. The need for a HIP process depends largely on the specific application and performance requirements of a MIM part.

Commenting on the reasons behind the growing use of HIP in the manufacture of MIM parts for the firearms industry, Dennis Poor, President of Kittyhawk Inc, a leading US provider of HIP services, told *PIM International*, "The obvious answer is that HIP will provide the end user with fully dense parts. That said it should also be noted that MIM can provide parts at a reduced cost, in a net or near net shape that eliminates or reduces machining costs and a fully dense part will have a significant positive impact on reliability, lowering field failures."

Poor noted, however, that there are a number of important considerations when considering the HIP of MIM parts, stating, "Many of the MIM components used in the firearm industry are small, thin walled, and have complex geometry making the part difficult if not impossible to straighten. It is therefore extremely important for the HIP provider to consider matching the correct cycle temperature to the part material and loading methods that reduce or eliminate distortion of parts. Diffusion bonding of parts loaded incorrectly must also be dealt with. Firearm parts also include an interesting and serious challenge to the HIP service providers as some parts have additional government regulations and controls requiring specialised licensing for 'any or all' entities handling the parts."

**Bringing HIP into the MIM plant**

Leading continuous MIM furnace manufacturer Cremer Thermoprozessanlagen GmbH, based in Düren, Germany, is developing a HIP system specifically for the processing of MIM parts. Ingo Cremer, the company's General Manager, told *PIM International*, "The MIM process is becoming more and more embedded in the weapons industry. In order to achieve the all-important dense and non-porous surfaces, HIP plays a key role. Part manufacturers, however, would much rather avoid sending components to HIP service firms, which takes a lot of time and adds cost. In addition, HIP service companies may be located in other countries and this requires the necessary knowledge of formalities, transportation modes and legal provisions."

Cremer added, "It is therefore becoming more and more important for the future development of the MIM industry to integrate the HIP process into the manufacturing chain of MIM parts as an essential link. It is obvious that we need to optimise plants with specifically adapted processes. Cremer Thermoprozessanlagen wants to play a role in this market with a new system that can process two production line sizes, 150 x 300 mm and 300 x 900 mm. Process time is reduced to a minimum thanks to the use of highly effective rapid cooling. The charge material is adjusted to the components and the maximum utilisation."

Cremer stated that as well as ensuring components reach full density, mechanical properties such as tensile strength and elongation are increased and machinability is improved, resulting in cost reductions for the whole manufacturing process, potentially helping MIM to replace forged and machined parts.

## MIM versus Investment Casting

As a division of the Spanish investment casting company Ecrimesa, Mimecrisa has the opportunity to see the changing balance between the use of Investment Casting (IC) and MIM technology in the firearms sector. Mimescrisa's Manuel Caballero commented, "For us MIM and IC are complementary technologies; there are parts that for their size or metallurgical characteristics must be IC and other parts that are without doubt MIM parts as you can achieve better tolerances and reduce machining costs."

"Most of the small parts, say under 50 g, such as safeties, triggers, hammers and even heavy duty internal parts have moved to MIM. Saving on machining operations and better surface finish compensates for the higher costs of the injection moulding tool. The competition is now in bigger parts for new designs, however frames or slides are still mostly produced by investment casting and machining."

IC still has the distinct advantage over MIM in that the cast parts can be bigger or heavier than the MIM parts. Batch sizes with MIM, however, can be significantly higher thanks to the speed of the process and limited requirements for finishing operations. MIM parts can also be produced with greater material and energy efficiency, without the need for manual finishing operations, with more design details such as embossed lettering, blind holes, slides and thinner walls. Other advantages for MIM include superior tolerance control for smaller dimensions and the need for less space for the injection point as compared with investment casting gates.

## CASE STUDY: Desert Eagle .50 AE

A case study that offers insight into the application of MIM technology into a firearm is that of Magnum Research's Desert Eagle .50 AE pistol. Founded in 1980, Magnum Research, Inc., based in Minnesota, USA, worked with US MIM manufacturer Phillips-Medisize Corporation to produce 12 of the 92 parts in the Desert Eagle .50 AE pistol by MIM [9].

This collaboration saw, for the first time, all components of the Desert Eagle pistol manufactured entirely in the United States. According to Todd Seyfert, Partner at Magnum Research, the move to domestic manufacturing of the Desert Eagle .50 AE not only reduced costs, but eliminated freight expenses and uncertainties around foreign currency exchange rates, as well as enabling

Fig. 14 MIM parts manufactured by Phillips-Medisize Corporation for Magnum Research's Desert Eagle .50 AE pistol (inset) [9]

Magnum Research to gain complete control of product quality and production and meet surges in market demand.

"Given the current economic climate worldwide and the loss of manufacturing jobs, we think it's important – even on our scale – to return manufacturing jobs to the United States. We're happy to be a part of this movement," stated Seyfert.

The material Philips-Medisize proposed for the MIM Desert Eagle parts was 42CrMo4, comparable to 4140 steel. "The material blued very well," stated Jim Tertin, Director of Manufacturing at Magnum Research, commenting on the way the material took to receiving black oxide treatment. "That's a big deal. Our guns have to shoot really well, but they also have to look really good. When we blue a part it can't turn maroon in a year. We blued, welded, and polished our test parts, and to this day, they're all still black."

Magnum Research provided Phillips-Medisize with Desert Eagle .50 AE part designs upfront and the two companies teamed together to work out dimension and tolerance issues to make the parts more manufacturable. The companies also identified a number of previously cast parts that could be Metal Injection Moulded. Phillips-Medisize created two multi-cavity moulds and eight single cavity moulds to make a total of twelve Desert Eagle .50 AE parts for Magnum Research. From start to initial part sample delivery, the development process took four months.

## CASE STUDY: MIM in Ruger's LCR® (Lightweight Compact Revolver)

In a keynote presentation given at MIMA's annual conference in 2012, and later reviewed in *PIM International* [10], Joseph J. Zajk, Chief Engineer, Pistols, at Sturm, Ruger & Co., Inc. offered an insight into the development of a new firearm and the factors that have to be considered before a component manufacturing route is selected.

Sturm, Ruger & Company, Inc., commonly known as Ruger® Firearms, was founded in Southport, Connecticut, USA, in 1949 by William B. Ruger and Alexander Sturm. Today the company is one of the US's leading firearms manufacturers.

Zajk explained that for over 50 years the company's famed reliability and value had largely been due to Ruger's expertise in precision investment castings and the process had become the company's technology of choice for producing small, intricate components. Investment casting is still at the heart of the company's component production capability with pistol barrels, slides, hammers, receivers, frames, bolts, hammer and triggers, to name just a few, all in high-volume production.

The trend towards more compact firearm designs with smaller, more intricate parts made investment casting these components challenging and Ruger turned to MIM to complement its expertise in investment casting. Zajk commented that William B Ruger Sr. once said, "The key is complexity of the component you are considering to make as an investment casting. If it isn't complex, the casting process is hardly beneficial." The same approach needs to be taken when applying MIM technology, suggested Zajk - if there's no complexity, there's no advantage.

Ruger's interest in MIM as a manufacturing process came at a time when the technology had reached the necessary level of maturity and the changing firearms market demanded smaller, lighter and more compact handguns that also offered performance improvements. Today, Ruger uses a select number of US-based MIM suppliers.

In 2009, Ruger introduced the LCR® (Lightweight Compact Revolver) (Fig. 15). This was Ruger's first clean-sheet revolver design in over 20 years and presented the company with the opportunity to design for MIM from the outset. Additionally, the revolver's small size and light weight meant that many of the components that the company traditionally investment cast were no longer a good fit for that process. Overall cost was also a concern, as Ruger was entering a highly competitive market. A number of MIM parts found application in the LCR®, as can be seen in Fig. 16.

One complex part from the LCR® was a star-shaped ejector. A MIM blank was produced that incorporated a deep through hole with a minimum draft. The requirement to gundrill and ream was eliminated and the hole established machining datum. Zajk stated that in this instance the MIM component required less machining than a casting, offered equivalent material properties and came in at a lower overall cost.

*Fig. 15 Ruger's LCR® (Lightweight Compact Revolver), introduced in 2009 [10]*

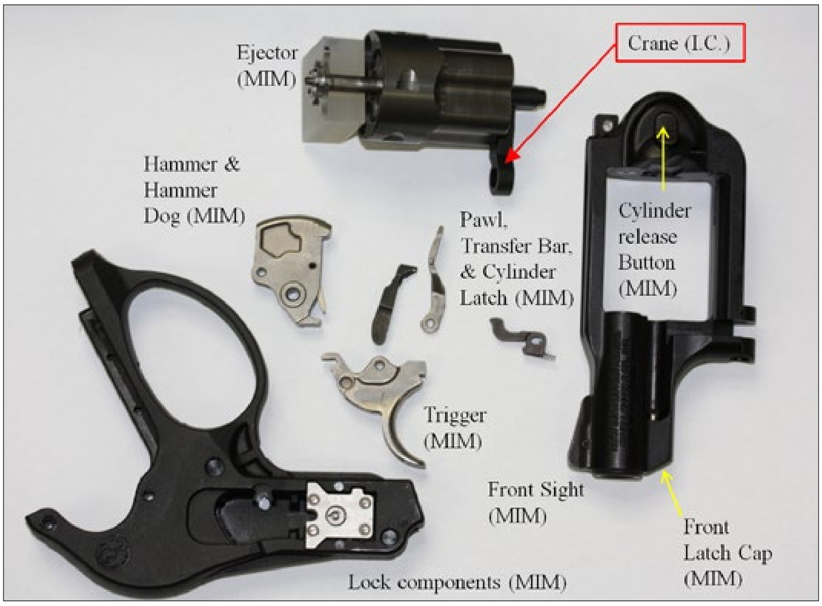


*Fig. 16 Many of the components in Ruger's LCR® were specifically designed for MIM production [10]*

## Outlook

From a stabilising domestic US firearms market to a European industry hit by political sanctions and government regulation, MIM suppliers to this sector are currently having to navigate uncertain territory. What is clear, however, is that the industry is firmly established as a valued partner for gun manufacturers and that there is no doubt that the use of MIM parts in firearms is set to increase as new guns are developed.

Looking to future challenges, Parmatech's Rob Hall told *PIM International*, "I see three primary areas of focus for the MIM industry to further grow the firearms market. Firstly, we need to continue to drive forward with MIM process capabilities in order to improve the performance and value of the firearms components. Secondly, we need to expand beyond core internal components to larger components such as slides, barrels and cylinders. Finally, it is vital that we work closely with the OEMs in the initial design phase to provide the full benefits of the MIM process."

From a US market perspective MIMA's Bruce Dionne stated, "The growth of the firearms industry in the US has greatly supported the growth of the MIM industry and vice versa. Growth to date has been unprecedented and those businesses that support it recognise the energy that political and civil unrest adds to the system. Fear continues to drive new would-be gun owners to gun shops across the nation and those that supply the industry are certainly aware of the volatility. There will continue to be opportunities in this industry brought on by new products and designs and, when we take out the noise and volatility that has been in the system, we still see a year on year growing industry with opportunities for the future."

ARCMIM's Kevin Schwindt stated, "MIM offers reduced costs to manufacturers of firearms parts and it's a well accepted manufacturing process within the industry. I think we will continue to push parts size limits and reduce the time for new product development - as well as faster manufacturing times for products. For the MIM supplier that can be low cost and has the faster development time to delivery first off parts, they will continue to be the supplier of choice to any customers."

Matt Bulger, Vice President

Technology at NetShape Technologies, Inc believes that new alloys and developments in processing techniques will also go a long way towards opening up new applications for MIM in the sector. Bulger stated, "Currently standard MIM materials cover a high percentage of the requirements desired by firearms manufacturers. Improved dynamic properties, especially fatigue and impact strength, will help extend the reach of MIM into new applications. With its ability to create a wide variety of alloy compositions and heat treatments, MIM is well positioned to meet increasing material property demands. This will be done through alloy improvements and secondary processes like Hot Isostatic Pressing. It is incumbent on the MIM producers to continue this push forward, with new standard developments and improved process control".

*'Improved dynamic properties, especially fatigue and impact strength, will help extend the reach of MIM into new applications'*

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# Dynacast International: US-based die casting specialist looks to become a global MIM front-runner

Dynacast International's announcement that it was moving into the Metal Injection Moulding business was one of the industry's biggest stories of 2013. Since then Dynacast has established two MIM operations, acquired one of North America's leading MIM producers and has been busy promoting its unique variant of the Metal Injection Moulding process. *PIM International's* Managing Editor Nick Williams profiles this latest member of the MIM community.

Dynacast International, the global die casting manufacturer headquartered in Charlotte, North Carolina, USA, has in the past two years made significant waves in the Metal Injection Moulding (MIM) industry. In February 2013 it announced that it was adding MIM to its service offering and by mid-2014 the company had operations up and running in both Elgin, Illinois, USA, and Singapore. This was followed in October by Dynacast's purchase of US MIM producer Kinetics Climax, Inc., based in Wilsonville, Oregon for $45 million. There can be no clearer signal that Dynacast sees major opportunities in MIM and its stated intention is to become one of the largest global suppliers of MIM components.

Dynacast has been manufacturing small and medium sized die cast components for more than 70 years using aluminium, magnesium and zinc alloys. By adding Metal Injection Moulding as a new service, the company believes that it is strengthening its commitment to producing the highest quality, precision-engineered components for its customers. Dynacast operates 23 manufacturing facilities in sixteen countries worldwide and has some 5500 employees. Results for 2013 showed net sales of $580 million, an 11.7% increase from the previous year.

Dynacast established its MIM production line during 2013 with investments in machinery and expansion of the company's existing facility in Elgin, as well as in Indonesia, which provides ancillary support services to the Singapore MIM operation.

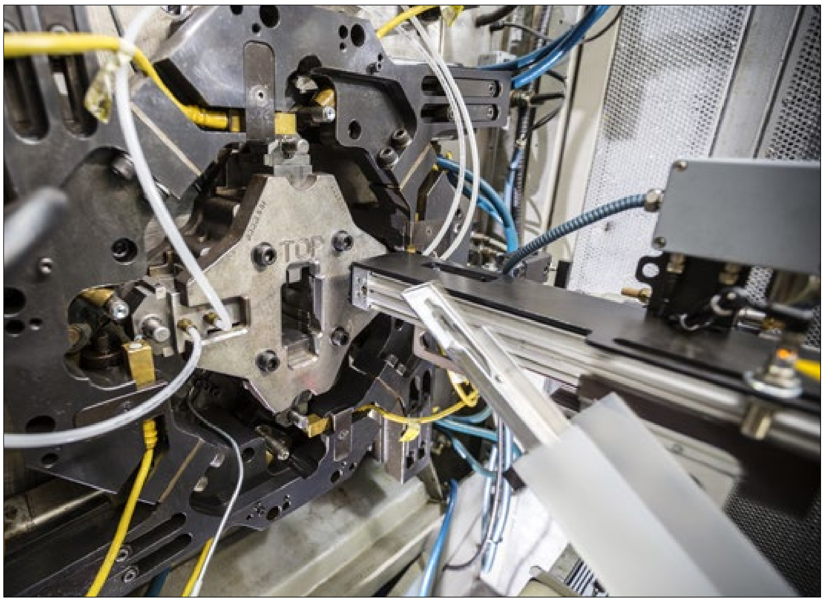

*Fig. 1 An A2 injection moulding machine at Dynacast, showing the company's unique multi-slide tooling*

  

*Fig. 2 Extruded MIM feedtstock at Dynacast prior to pelletisation*

*Fig. 3 MIM components loaded in baskets for solvent debinding*

## Dynacast's variant on the MIM process

A key factor behind the move into MIM was Dynacast's development of its own variant on the MIM process which, the company states, increases productivity while reducing variation and costs. The company modified its proprietary A2 die-casting machine to make it compatible with MIM feedstocks, enabling the use of the company's multi-slide tooling system. This system employs a set of sliders that converge in the die block to create the cores, cavity and runner system. Conventional MIM tools, by contrast, arrange the cores, cavities and runners within two opposing mould halves. The result, states Dynacast, is a decrease in cycle times and increase in productivity with improved part-to-part consistency and tighter tolerances.

Dynacast's Chief Sales Officer, Tom Kerscher, told *PIM International*, "We would only enter a market in which we believe we have a true competitive advantage. We see multi-slide MIM as a pivotal part of that advantage. It took us three years to develop the technology and we did not enter the market until we knew we were ready."

Commenting on the advantages of the A2 machine for MIM parts production, Kerscher stated, "A2 machines and multi-slide tooling produce faster cycle times - up to six times faster than standard moulding machines. Using our already established tooling expertise results in lower tooling prices and shorter lead times. A further advantage is that the feedstock is heated much closer to the tooling cavity, enabling shorter runner systems and thus less material residence time in the machine."

The process of adapting the machines to process MIM feedstock, stated Kerscher, was relatively straightforward. "Utilising the A2 machines to produce small MIM parts was our goal from day one. With 70 years of designing and building our multi-slide technology we had little to overcome. The feedstock feeding system had to be designed and integrated into the logic of the machine. Other than minor modifications, the machines can be converted from zinc to MIM in under two weeks."

## Advantages of the A2 machine

Dynacast has been building multi-slide tooling since 1936 and still today all of its tooling is manufactured in-house. With the faster cycle times, the company claims that fewer cavities are required to meet production needs, thereby keeping costs down. On small parts an A2 machine can produce parts at up to twelve cycles per minute. Cooling, it was stated, is the limiting factor to faster cycle speeds. The main reason for the A2's lower cycle time is that the die casting-type feeding system eliminates the time required by a conventional moulding machine's barrel and reciprocating screw to inject the MIM feedstock into the tool and recover for another shot.

"Whilst a standard four cavity injection moulding tool can produce around 2.5 million parts per year based on twenty hours of production a day, five days per week, an A2 single cavity tool can produce around 3.1 million parts. Using a single cavity versus four also results in reduced variables and easier qualification," commented Kerscher.

Dynacast states that for the manufacture of a precision sporting goods component its MIM process achieved a 1.67 Cpk on a key print tolerance of +/- 25 µm (0.001 inches), equivalent to just one out of tolerance event per million parts. "By using fewer cavities we have eliminated a major variable."

The company told *PIM International* that tooling used for die casting, which is a much harsher environment, has produced over one million shots without cavity replacement. Commenting on feedback from customers, Kerscher stated, "This has been overwhelmingly positive. When a customer sees the advantages of multi-slide from the standard MIM process, it is easy for them to realise the benefits to both their end product and their bottom line."

The A2 system does, however, have part size limitations compared with conventional MIM tooling, with A2 parts limited to a maximum weight of 14 g.

*Fig. 4 Green MIM components prior to sintering*

*Fig. 5 Centorr Vacuum Industries MIM-Vac furnaces at Dynacast's Singapore MIM operation*

## Materials development at Dynacast

Although injection moulding using Dynacast's A2 system differs significantly from conventional Metal Injection Moulding, the debinding and sintering steps are the same as for conventional MIM processing.

Dynacast invested significant resources into the development of its proprietary MIM feedstock. The company uses a solvent debinding process that removes 99% of the primary binder prior to sintering. This process can take between two to four hours depending on the size of the part. This includes a drying process that ensures all solvent is removed from the component.

Kerscher explained, "We start our feedstock manufacturing process by analysing the incoming metal powders using a MicroTrac machine that measures particle size, checks oxygen and carbon levels and densities. We use these data in our formulae so each batch of material meets specific shrink factors and characteristics known for that alloy. We then mix our material in 50 lb canisters that provide very tight controls of the ingredients. The powder and binder mix is then blended for fifteen minutes before being added to a Leistritz extruder where the material is heated and pelletised. During this process, numerous samples are taken and tested for the theoretical density of the powders and binders specific to the type of feedstock."

Dynacast currently processes the most common MIM materials including 17-4PH, 316L and 420 stainless steels, 4605 low alloyed steel, 4140 high tensile steel and copper. "As we continue to grow and our customers require different materials we will add them. This is the biggest advantage of compounding our own material. We can custom blend materials to match their requirements." The company states that it uses both master alloys and pre-alloyed powders.

Commenting on the motivation for developing a proprietary feedstock

*Fig. 6 Maintaining multi-slide MIM tooling at Dynacast*

system rather than buying a proven feedstock system from an established supplier, Kerscher stated, "There is one major supplier of feedstock that can support the global market. We choose to produce our own feedstock so we can control the quality, consistency and cost of the finished material. Our feedstock meets the MPIF Standard 35 Material Standards for Metal Injection Molded Parts and we can offer a wide range of alloys and can custom blend to customer's specifications."

The sintering process varies depending on the alloy. "Our furnaces vary from using molybdenum or graphite retorts for specific alloys and we produce our own nitrogen and hydrogen sweep gases with in-house generators allowing clean and higher purity gas. The average cycle time is 14-16 hours." Dynacast currently uses batch vacuum sintering furnaces from Centorr Vacuum Industries and G-M Enterprises, however the company states that investment in continuous furnace technology remains an option for the future.

Post-sintering operations available in-house at Dynacast include CNC machining, coining, tapping and reaming and assembly. Plating and heat treatment are outsourced.

## Markets and regions

In terms of major growth markets for its MIM business, Dynacast sees automotive applications as a major growth area internationally, particularly in fuel management and turbocharger systems. In Asia growth is still anticipated in the consumer electronics market, whilst in the US the sporting goods sector continues to be important. It is, however, the medical sector where the most rapid growth is taking place. "Medical components are getting smaller and much more complex, perfect for multi-slide manufacturing," commented Kerscher.

The company sees the European automotive industry as being of particular interest for its MIM business, where it sees significant potential thanks to Europe's heavy use of turbocharger systems.

With MIM operations in both Asia and North America, Dynacast's operations vary according to the nature of the markets served. "MIM has always been challenged in terms of lead times and the industry is continuously looking for ways to improve. Our Singapore facility is accustomed to extremely short lead times and short product life cycles. Here in the US we often use automation for secondary operations, whereas in Singapore and Indonesia we can use our flexible labour force to do the same work but without the lead times needed to build the equipment."

Dynacast sees itself as being in a strong position by offering a choice of manufacturing technologies. "Dynacast's advantage over our competition is that we offer both MIM and die casting. Quite often a customer specifies a MIM material but after digging deeper we discover that zinc, aluminium or magnesium is a better material and a less expensive option. On the other hand, some customers may currently have a die cast component that is not meeting their physical requirements so we can then offer a stronger material using MIM," Kerscher stated.

The company also believes that its size brings advantages. "With our global reach, 23 facilities in 16 countries, we can provide opportunities that other MIM companies cannot. Industry-leading customers are looking for suppliers who are accustomed to dealing with companies similar to themselves. We believe that we are the best choice thanks to our long history, industry knowledge, tooling expertise, and diversified customer base."

## The acquisition of Kinetics

In October this year Kinetics Climax, Inc., one of the largest MIM companies in North America based in Wilsonville, Oregon, became a wholly owned subsidiary of Dynacast International Inc. This acquisition adds significantly to Dynacast's capacity to manufacture larger MIM parts that are beyond the size range of its A2 process, as well as bringing significant expertise gained over more than thirty years of MIM production.

Commenting on the motivation behind the acquisition Dynacast told *PIM International*, "We would like to expand our Metal Injection Molding capabilities and Kinetics is a North American leader in the industry. Kinetics' experience in complementary markets, including the medical and automotive industries, aligns with Dynacast's expertise and the acquisition is expected to be a mutually beneficial relationship for both companies and their customers."

Simon Newman, Dynacast's Chief Executive Officer, stated at the time of the announcement, "This acquisition establishes Dynacast not only as a premier precision component manufacturer globally, but also as a front-runner in the growing Metal Injection Moulding market."

Dynacast believes that its in-house tooling expertise and design innovation will enhance Kinetics' MIM manufacturing processes. In turn, by leveraging Kinetics' technology and MIM experience, Dynacast states that it will be able to accelerate the development of its own existing MIM operations, offering greater value to customers and securing its position as a leading multi-faceted supplier in the global precision metal marketplace.

Dynacast states that there is no intention to use its A2 technology at Kinetics. Kerscher commented, "We have no intention of changing equipment on current and ongoing Kinetics projects. The A2 system is ideal for parts that are approximately 14 g or smaller and have highly complex geometry. We will help customers select the process that makes the most sense for their project – whether it's in the A2 or the standard moulding machine. There is no immediate strategy to replace existing business to A2 tooling but if there's a competitive advantage to changing tools, we're open to discuss."

Kinetics produces over 60 million MIM parts annually out of its 5100 $m^2$ plant, which operates 24 conventional Engel injection moulding machines with clamping forces ranging from 40 to 125 tons. In addition to MIM parts production the plant features six CNC machining centres as well as capability for the rapid production of prototype MIM parts using the company's QuickMIM™ process.

This system uses prototype tooling combined with production injection moulding machines and debinding/sintering furnaces, to significantly reduce tooling costs and lead-times. Production grade feedstock is also used and a quick turnaround time of 21 days for up to 500 as-sintered parts is offered. Standard materials offered include 17-4PH, 316, 420, 12Cr, 4605 and 420Nb.

*Fig. 7 2011 MPIF award winning 17-PH stainless steel distal channel retainers manufactured by Kinetics. The complex, multi-level part is the main distal-side component of an articulation joint in an articulating mechanical stapler/cutter used in endoscopic surgery*

## Looking to the future

What is clear is that Dynacast is looking to be a world leader in MIM. Kerscher told *PIM International*, "Our vision is to be the largest MIM supplier in the world. We are already operating MIM plants on two continents and, if the market dictates, we will add MIM to one of our European facilities."

"Being a global company with a global sales force allows us to react quickly to our customers' needs. We can be at our customers' facility whenever they need assistance and our sales team is knowledgeable about all of our processes and can offer the best solution for any given application."

It is clear that Dynacast has made significant progress towards realising its MIM ambitions over the past two years. By modifying its A2 machines for MIM, and through the acquisition of Kinetics, the company is proving that it sees major opportunities in the MIM market and is committed to growing that part of its business. With a continued focus on MIM, Dynacast is positioning itself to not only be a premier precision component manufacturer but also a front-runner in the MIM industry.

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# Considerations when transitioning from plastic to Metal Injection Moulding

Much of the growth in Metal Injection Moulding (MIM) capacity has come from established component manufacturers from other industries expanding their production capabilities to include MIM. Whilst those from a metals background will benefit from a reasonable understanding of metallurgy, those from a plastic injection moulding background will have a very limited understanding of exactly what happens once a MIM part is ejected from the mould. In this article Dr Satya Banerjee, DSH Technologies, shares some of his extensive experience as a MIM industry consultant.

Many North American and European plastic injection moulders are facing increased competition as more manufacturing moves to countries with lower operating costs. Metal Injection Moulding (MIM), which has been growing at a double-digit rate for many years, is an opportunity to be explored.

For some, the transition to MIM is like moving from the known hazards of the warm tropics to the unknown slippery slopes of a winter ski resort. Luckily, with a little help this challenge can be an enjoyable drink by the fire instead of a careening death slide down an icy slope. To do this right, without the costly process of learning from your mistakes, many companies will rely on an experienced consultant in the industry who is prepared to help them all the way through this transition.

MIM can be seen as the marriage between plastic injection moulding (IM) and Powder Metallurgy (PM). There are fundamental similarities between plastic injection moulding and MIM. In each case, the raw material is moulded using a conventional injection moulding machine to make the basic part. In MIM, parts can be manufactured using a diverse range of materials, from low alloy steels and stainless steels to copper, titanium and even aluminium. As can be seen in Fig. 1, part sizes can range from micro-components to parts weighing more than 250 g.

The plastic injection moulding community is accustomed to shooting the material and obtaining a part that

*Fig. 1 This selection of EPMA award winning MIM parts not only shows the shape capabilities of the MIM process, but also the variation in part size. Parts shown range from an extremely small 316L eyewear hinge part weighing just 0.028 g to a photographic tripod component weighing 260 g*

Fig. 2 The top image shows a sintered MIM demonstration part along with granulated MIM feedstock ready for processing. The lower image shows the same part in the as-moulded "green" state (left), in the "brown" state following first stage debinding (centre) and in the as-sintered state (right)

is ready to ship. However, for MIM, the injection moulded part is the starting point. A few more processing steps are needed before the final part is produced; a fact which frightens away many would-be MIM part makers. These steps are not insurmountable, but in order to transition to MIM it is necessary to understand the differ-ences between the two processes.

In MIM, the only use of the plastic components within the feedstock is as a carrier to fill the mould. After moulding these "binders" are removed in stages until, under heat, bonds between the powdered metals are formed, enabling retention of the moulded shape. During this process the part shrinks by a predetermined exact controllable amount (Fig. 2). The consistency of the binder and the metal powder contents, as well as the volume ratio of the binder to metal powder, must be consistent and accurately repeatable in order to produce parts with dimensional and structural uniformity from lot to lot.

## Understanding MIM feed-stock

MIM feedstock behaves like a highly filled plastic containing a large amount of fine glass or ceramic particles. In this respect the materials for the IM and MIM processes are similar and the plastic injection moulder must now adapt to the other differences between IM and MIM.

The feedstock is a complex mixture of binders and metal powders made with the exact volume fractions of the different materials to ensure an exact repeatable linear shrinkage. In general, feedstock for MIM is 60% metal powder by volume. Shrinkage typically varies from 16% to 22% depending on the material and part. The variation in the shrinkage is typically held to better than ± 0.025%. Not only must the feedstock be made to the correct shrinkage with a tight tolerance, it must also flow the same and react the same when used for injection moulding.

The binder in the feedstock is made up of several components. Typical binders have the following constituents:

- A wetting agent that allows the binder to wet the metal surface and reduce the surface tension between the two
- A constituent that can be removed first from the mixture whereby a network of pores are opened so that the rest of the binders may come out easily. The wax in a wax-based feedstock is easily dissolved in a solvent, opening up the pores. When using a POM based catalytically debound feedstock, such as BASF's Catamold, the polyacetal breaks down in the presence of nitric acid around 115°C creating pores from the outside in
- A secondary binder that holds the powder particles together until the particles begin to form bonds by diffusion
- A material that allows the primary binder to wet and mix with the secondary binder.

The metal powder can be pre-alloyed, a mixture of elemental powders, or a base powder with a master alloy. For every powder a certain minimum amount of binder is necessary before the feedstock will flow. Also, particle size, particle size distribution, powder morphology and shape affect the flow of the feedstock.

The resulting interactions are difficult and complex. Although they can be learned, it is suggested that during the start-up phase, newcomers who have a background in IM but not one in Powder Metal-lurgy buy the feedstock from one of the several commercial feedstock manufacturers with a reputation for making consistent products. Once a firm is past the learning curve in this new technology and is confident with the MIM process, they may find it more cost effective to produce their own feedstock in-house.

  

## Mould design considerations

The MIM mould has several differences from standard plastic injection moulds. Most importantly, MIM moulds are 16% to 22% larger than the actual part. The exact percentage depends on the feedstock, where the shrinkage factor in the feedstock is maintained to a close tolerance level. The shrinkage factor depends on the choice of the feedstock, which depends on the size and the details within the part to be produced and the volume fraction of binder in the feedstock.

Metal powders have higher heat conductivity than plastic and so the MIM feedstock cools faster than plastic parts. Hence gate sections need to be larger and, for certain feedstocks, the moulds need heating.

The densities of the plastic binders are a few times lower than those of the metal powders. Rapid velocity changes of the molten feedstock within the mould may cause the powder to separate from the binders and lead to dimensional and/or density variation in the sintered part. Therefore, in the design phase, sharp turns and sharp corners must be avoided and heavy sections cored out whenever possible.

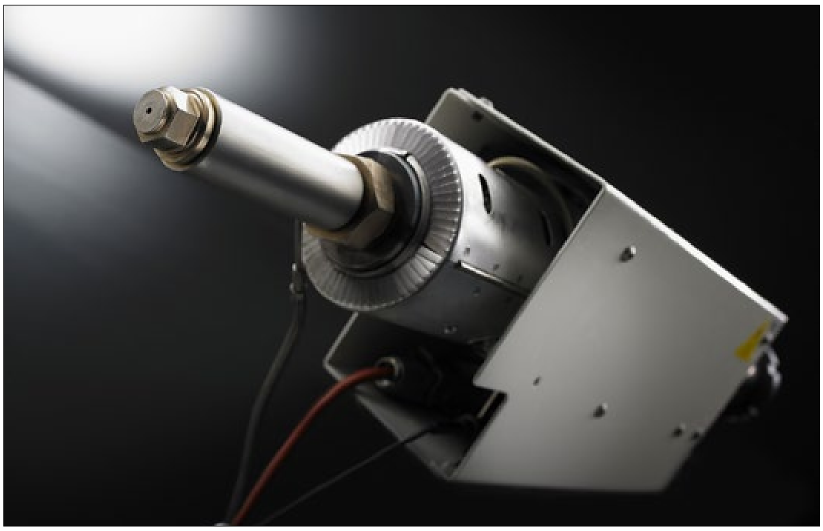

*Fig. 3 An elongated PIM nozzle penetrates deep into the mould, enabling sprues to be efficiently shortened (Courtesy Arburg)*


*Fig. 4 A modern solvent debinding furnace (left) with a solvent recovery system (centre) and control unit (right) (Courtesy LÖMI)*

## Injection moulding

A typical MIM feedstock can be seen in the upper part of Fig. 2. Because the feedstock contains approximately 60% by volume of metal powder, it is darker than a typical plastic and can be very abrasive. The moulding machine therefore needs to be equipped with hardened barrels, screws, tips and check rings. The check ring must have a larger amount of clearance to permit more than one time (typically three times) the largest metal powder particle in the feedstock. The typical MIM screw has a compression ratio of around 1.5 compared to about 2 for that for IM. An elongated PIM nozzle also helps reduce sprue length (Fig. 3). Moulding machines specifically adapted for MIM are available from a number of international suppliers.

Moulding, barrel and nozzle temperatures, as well as mould temperatures will vary, depending on the feedstock used. BASF's Catamold feedstock requires a high barrel and mould temperature, unlike other feedstocks, which require temperatures that are significantly lower.

At the end of the moulding cycle a cushion is a must to make up for the shrinkage caused by the temperature drop during solidification of the feedstock and to avoid sink marks in the part. The reversal of the screw to fill up the barrel at the end of the cycle is as slow as possible to prevent binder separation.

At the end of the process it is necessary for the part to have the same density as that of the starting material. Any degradation of the feedstock will cause the part to have a different shrinkage rate. Voids in the part will also result in a lower density. Voids may be avoided by using proper venting techniques or vacuum evacuated moulds with optimum moulding conditions.

The runners and gates may be ground up and reused, either directly or by mixing with virgin material.

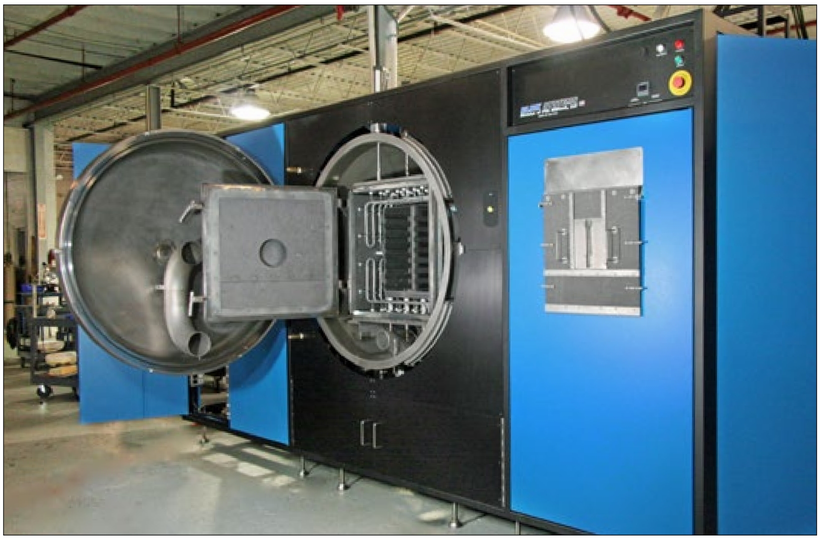

*Fig. 5 A GraphMIM 3045 series MIM vacuum furnace manufactured by Elnik Systems*

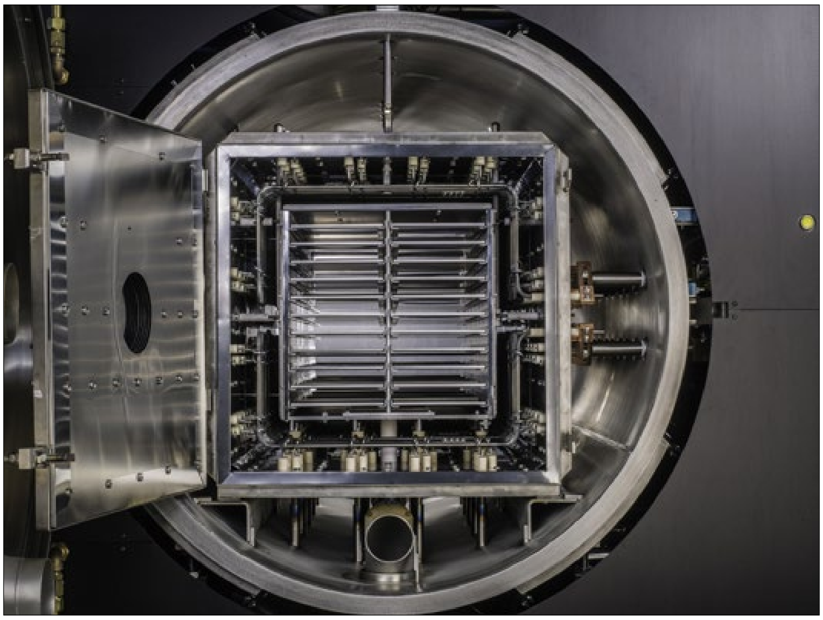

*Fig. 6 A view of the molybdenum hot zone in a MIM 3045 series furnace manufactured by Elnik Systems*

Feedstock density measurements may be used to ensure that the regrinds are still within the tolerance limits that provide acceptable dimensions of the parts.

## First-hand insight from a plastic moulder

One company that has successfully navigated the transition to Metal Injection Moulding is Proto Labs Inc., headquartered in the US. Rick Bigaouette, Director of Development at Proto Labs, commented on the main differences that he noticed between the processes. "MIM parts tend to be more brittle than plastic parts, so extra care should be given to designing the ejector system. The quantity and placement of ejector pins will help ensure the parts can be ejected without breaking. Adding draft to part walls and additional polishing of the mould surfaces can also help to reduce damage to parts due to ejection," stated Bigaouette.

"Lower back pressure and screw speeds are helpful in reducing segregation. MIM material tends to be more prone to flashing, so tight parting lines on the mould are critical to minimise this effect. Trapped gas is less of an issue with MIM than plastic, so venting is not as critical."

Bigaouette also stated that,"MIM materials are not as sensitive to sink as most plastic materials, and mould polishing is more important from a release perspective as many finishes do not translate to the finished part."

## Primary debinding

The purpose of the primary debinding is to open up passageways for the secondary binder to come out. Depending on the feedstock, there are several types of primary binders which may be used. They include:

- A polyacetal, which decomposes in contact with acid
- A wax like substance, which can either evaporate on slow heating (the original technology) or be dissolved using a solvent (the faster and preferred technology)
- Water soluble polymers such as polyethylene glycol, polyvinyl alcohol, saccharine, sugars and starch, etc.
- Water which combines with an ingredient to make a mould-able material and needs to be evaporated before the parts are put in the furnace.

Each feedstock type has its advantages and disadvantages. The feedstock type should be chosen carefully depending on the part to be moulded. It is up to the manufacturers to choose which feedstock works best for their purposes. A modern solvent debinding unit is shown in Fig. 4.

## Secondary debinding

The purpose of the secondary binder is to hold the particles together until bonds form between the metal powder particles which cause the shape of the part to be retained after the polymeric binders are removed.

The technology currently employed heats up the part in a protective atmosphere, allowing the binder to evaporate slowly. The secondary binder vapours escape through the fine pores which have been opened by removing the primary binders. A slow ramp and a hold at a temperature where the binder evaporates are necessary to achieve this goal. The hold must be long enough to evaporate all the binder from the part. If the binders evaporate too rapidly the part will distort or disintegrate, because at these temperatures the bonds that are formed between the metal particles are tiny and rupture easily. The parts at this stage are extremely fragile - just a touch is enough for the parts to crumble into powder.

## Sintering

The concept of sintering is difficult to comprehend for those with little background in materials. At the atomic level, all materials move in the solid state. After a certain temperature is reached, the movement of the atoms cross particle boundaries and bonds are formed between particles. At high temperatures, in most cases below the melting point of the alloy, pores between the particles are eliminated and one solid body is formed. This is a highly simplified explanation of sintering.

In the early days of the MIM process parts were presintered to about 1100°C after secondary debinding. After this, they were strong enough to be handled and reset to be put into another furnace for the final sintering step. Today very few operations use this method and secondary debinding and sintering is done in one furnace to save time and money. After sintering the part looks metallic. It has densified and shrunk by about 40% by volume, depending on the exact volume percentage of the binder present in the MIM feedstock. Fig. 5 shows a typical MIM sintering furnace, in this case fitted with a graphite hot zone for iron based parts. The hot zone of a similar furnace with a molybdenum hot zone for more advanced materials can be seen in Fig. 6.

## Quality management in MIM

It is essential that the flaws in the parts be caught during the moulding stage because up to this point the

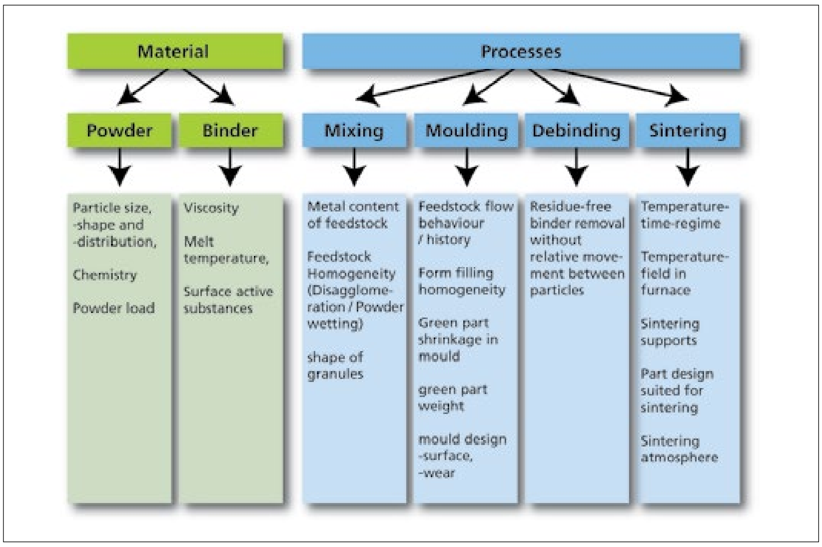


*Fig. 7 Possible factors influencing the final quality of MIM components (As published in"Managing quality in the complete Metal Injection Moulding process chain", PIM International Vol. 8 No. 2 (2014), 37)*

defective part can be ground up and reused. Flaws that are not identified right after moulding will end up in the finished part, which may have to be scrapped. Fortunately, defects in the green state are easily detected by measuring the density of the green part and comparing it with that of the feedstock.

A detailed list of factors that need to be considered when trying to understand MIM part quality can be seen in Fig. 7.

## Making the transition

It is time to venture out into that ski slope and a consultant is like a ski instructor who can help you to transition as you make your way down the first hill. Choosing a consultant with many years of experience with newcomers to the Metal Injection Moulding industry makes them the ideal partner for your company.

They can help you determine the best kind of feedstock for your purposes and provide you with a list of well-known suppliers. Perhaps most importantly, they will advise in the pre-production stage to develop the final mould dimensions. Often complex parts require one or more iterations of the mould for the part shrinkage to be perfect. Start by moulding the parts in-house and sending them out to a consulting firm who can also debind and sinter production quantities of parts.

When you are ready to move production in-house, the consultant should be able to help you set up your manufacturing plant, in everything from machinery to employee training for the day to day production. For each of the steps required, DSH Technologies has the experience and knowledge to make your transition smooth.

## Acknowledgements

We would like to thank Rick Bigaou-ette, Director of Development, Proto Labs, Inc., Maple Plain, Minnesota, USA, for reviewing, providing input and the pictures used in this article. Proto Labs, Inc is a prototype and low volume plastic moulder who has successfully added MIM as an additional service to their customers.

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# PIM at Euro PM2014: Emerging applications, material developments and advances in process modelling

The EPMA's Euro PM2014 congress, held in Salzburg, Austria, from September 21-24, provided an opportunity for the global PIM community to once again present its latest R&D activities. In this, the first of our reviews from Europe's leading PM event, Dr David Whittaker reports for *PIM International* on a number of interesting new applications for PIM, as well as developments in materials and modelling software.

## Emerging applications and opportunities for PIM

A number of technical sessions at Euro PM2014 provided an opportunity for presentations focused on emerging applications for PIM. Two papers in particular highlighted the potential for PIM in the green energy generation sector.

**Manufacturing and microstructure of porous metal supports for a Solid Oxide Fuel Cell**

The first of these papers came from Harald Gschiel, Christian Gierl-Mayer and Herbert Danninger (Technical University Wien, Austria) and Per-Olof Larsson and Hilmar Vidarsson (Höganäs AB, Sweden) and included PIM among a number of candidate Powder Metallurgy (PM) process routes for the manufacture of porous metal supports for a Solid Oxide Fuel Cell (SOFC).

One of the major drawbacks of a SOFC is long-term stability. In order to attain mechanical stability the cell can be supported either by the electrolyte or by a so-called porous metal support (Fig. 1). In the case of a metal-supported fuel cell (MS-SOFC), a thin film cell is deposited on top of this metal support. The load bearing part of the MS-SOFC is a highly porous Fe-Cr alloy and has a thickness of about 1 mm.

These metal supports are usually manufactured by tape casting. The reported work, in contrast, was focused on processing these supports by different PM techniques such as the press-sinter route, gravity sintering or Metal Injection Moulding.

In the MIM trials, an Fe-16Cr powder was mixed with high density polyethylene (HDPE), paraffin wax and

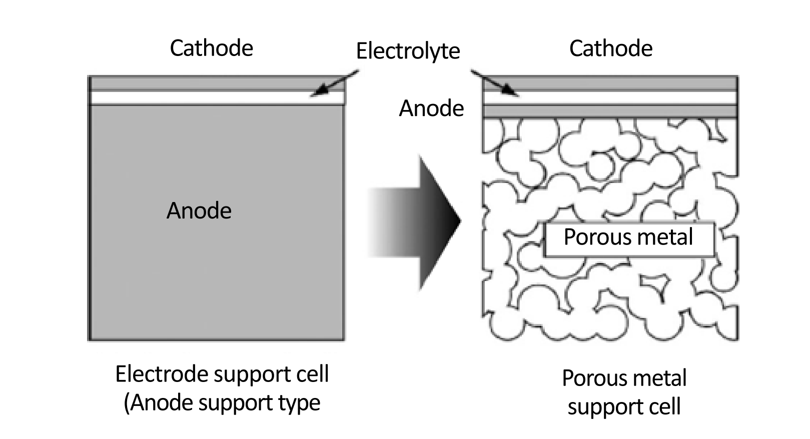


*Fig. 1 Schematics of an anode supported cell and porous metal supported cell [1]*

  

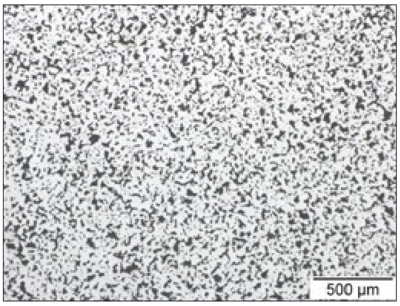


*Fig. 2 MIM Fe16Cr + 45 vol% powder loading, horizontal plane, 50x, 28% porosity (1300°C, vacuum, 60 min) [1]*

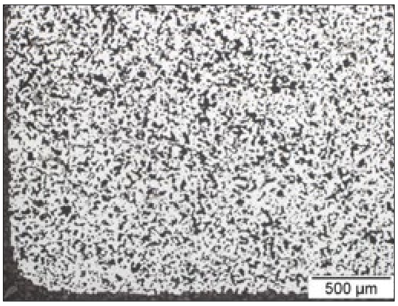


*Fig. 3 MIM Fe16Cr + 45 vol% powder loading, cross plane, 50x, 28% porosity (1300°C, vacuum, 60 min) [1]*

stearic acid, the composition of the feedstock being shown in Table 1. The debinding stage was carried out in two steps, solvent and subsequently thermal, and then the samples were sintered at 1300°C for 1 hour in high vacuum.

In MIM processing, the shrinkage in sintering was isotropic (Table 2). The isotropic shrinkage was not dependent on the powder loading, which was in the range from 45 - 55 vol%. As can be seen in Figs. 2 and 3, the distribution of the pores for the ferritic samples is very good. No agglomeration of pores is visible even for the lowest powder loading of 45 vol% and fine porosity can be seen in both plane directions (horizontal and cross section).

Overall, the most promising manufacturing routes were found to be gravity sintering, with about 50% porosity, and MIM, with 20 – 28% porosity. In both cases, the pores were homogeneously distributed and only slight agglomeration of pores could be seen. This offers good potential for co-sintering together with the other SOFC layers, although this remains to be assessed experimentally.

It is expected that these types of fuel cells will be competitive in the power generation equipment market because of their strength, tolerance to rapid thermal cycling and the reduced material costs that the metal support allows.

**Material development dedicated to thermo-electric generators for high temperature applications**

The second paper, from P Revirand, G Mauguen and M Bailleux (CEA-Liten, France), A Galnares (GDF-Suez, France), A Cabot (IREC, France) and J R Morante (CIDETE, Spain), assessed the potential of PIM for the manufacture of components within a thermo-electric generator for high temperature application.

The main objective of the reported work was to prove a new concept for waste heat recovery using a high temperature thermo-electric generator (TEG) device. Currently, TEG devices have significant limitations, related to the thermo-electric properties of the Bi-Sb-Te-Se alloys in use and to the manufacturing costs of various components in the device. The first of these limitations was tackled by the evaluation of CoSb3 skutterudites as materials with superior thermo-electric response. This development is, however, beyond the scope of this report.

The attack on the second limitation involved the development of low-cost manufacturing technology based on the convergence of various processes, namely Powder Injection Moulding, Hot Pressing, Spark Plasma Sintering and Inkjet Printing. The design of the demonstrator devices produced is shown in Fig. 4. PIM has been evaluated for the manufacture of the ceramic and conductive heat sink components within this design. In order to achieve a high level of energy conversion, the thermal conductivity of ceramic parts must be low. With the use of such an insulating material, the thermal energy flux is driven through the thermo-element materials. With a theoretical thermal conductivity close to 4W/m.K, alumina was identified as a promising material for the application developed within this project.

Various samples were produced and the thermal conductivity characterised to adjust the process parameters to the specifications required through an optimisation of sintering temperature. The thermal conductivity of samples, at 60% of full density, made by the Ceramic Injection Moulding (CIM) process and, after debinding and sintering at low temperature, was around 4 W/m K, whereas, for a fully dense material, 32.9 W/m K was obtained.

| Powder | Composition feedstock (vol%) | | | |
|---|---|---|---|---|
| | Powder | HDPE | PW | SA |
| Fe16Cr | 55 | 21.35 | 21.35 | 2.3 |
| Fe16Cr | 50 | 23.75 | 23.75 | 2.5 |
| Fe16Cr | 45 | 26.1 | 26.1 | 2.8 |

*Table 1 Feedstock for the MIM samples [1]*

| Sample | Powder loading (vol%) | Green density [g/cm³] | Sintered density [g/cm³] | Porosity [%] | Shrinkage length [%] | Shrinkage width [%] | Shrinkage height [%] |
|---|---|---|---|---|---|---|---|
| Fe16Cr | 55 | 4,54 | 6,19 | 20 | 13,3 | 14,5 | 13,9 |
| Fe16Cr | 50 | 4,32 | 6,10 | 22 | 13,5 | 13,6 | 11,0 |
| Fe16Cr | 45 | 3,97 | 5,59 | 28 | 13,4 | 14,8 | 12,8 |

*Table 2 Shrinkage and density of the vacuum sintered MIM samples (1300°C, 60 mins) [1]*

The ceramic parts, produced by CIM, are shown in Fig. 5. An improvement of the technology (patent in progress), was developed in order to produce more complex components with a curved shape able to be adjusted to a large panel of surfaces (Fig. 6). In order to evaluate the homogeneity of the component produced, computed tomography has been used. CT reconstruction has been carried out on the curved component and the analysis did not show any evidence of cracking.

The conductive heat sink was manufactured by MIM of a pure copper material. Fig. 7 shows this component in the green and sintered conditions. The shrinkage during sintering has been taken into account during mould design and the final as-sintered dimensions were very close to the initial objective.

Within the overall project, two demonstrators (high and low temperature devices) have now been produced and evaluated in real conditions.

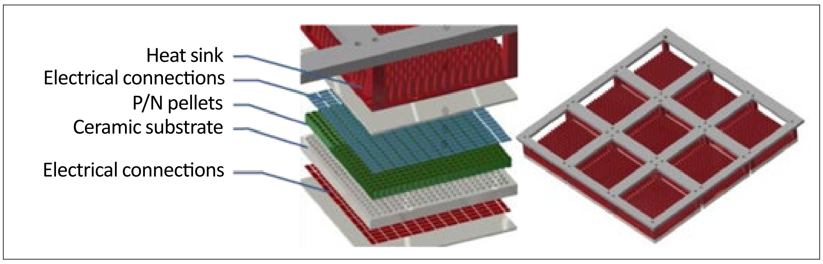


*Fig. 4 Design of the TEG device [2]*

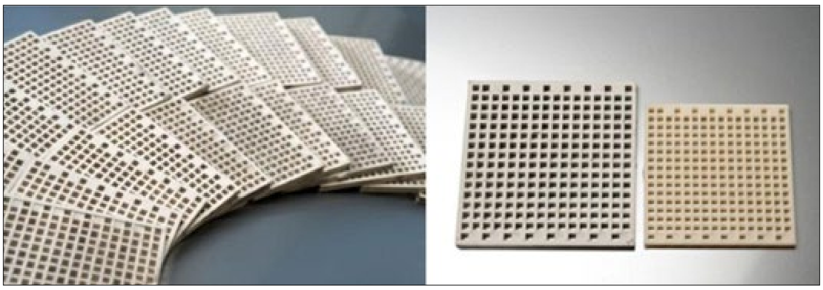

*Fig. 5 Ceramic parts produced [2]*

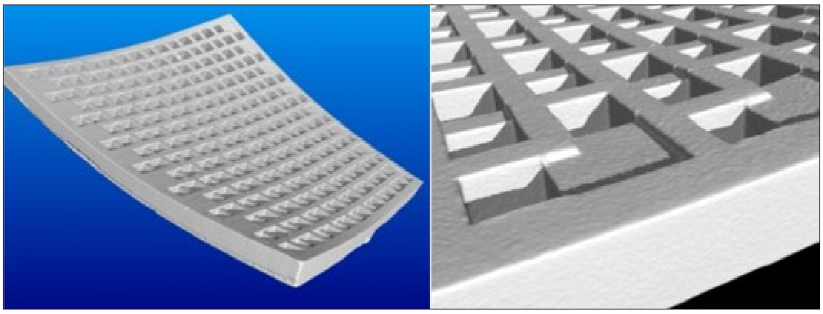

*Fig. 6 Computed Tomography reconstruction [2]*

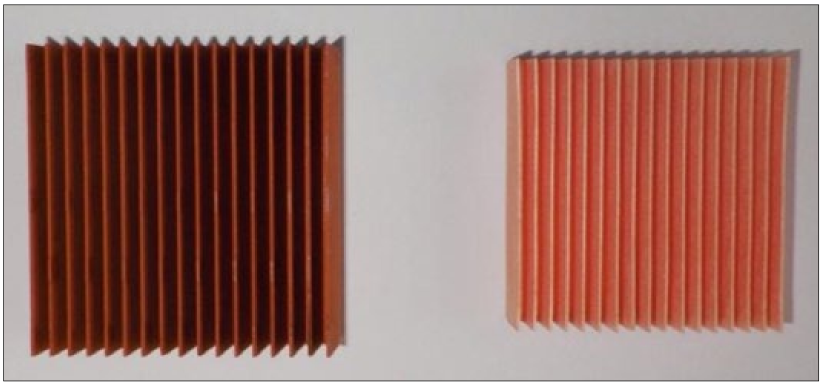

*Fig. 7 The Cu heat sink component, before and after sintering [2]*

## Material developments

**Aluminium MIM: Achieving higher strength using alloyed powder grades and a new feedstock optimised for MIM**

Jessu Joys and Clive Ramsey (United States Metal Powders Inc., USA) reviewed the company's development of a new aluminium alloy-based feedstock, optimised for MIM.

Aluminium MIM was introduced more than a decade ago but has never achieved significant growth, the major barriers to up-take having been identified as the relatively low achieved strength levels, difficulties in sintering and the lack of a feedstock that the part maker can process easily. The paper discussed the development of a feedstock comprising newly designed pre-alloyed aluminium powder grades that give excellent mechanical properties when combined with a newly developed binder for MIM processing.

The major challenge in the sintering of aluminium or aluminium based powder is the steady surface oxide layer coating with a thickness of approximately 4 nm on the powder, which needs to be reduced to attain good interparticle contact. Several methods have been discussed in the past and incorporating small amounts of magnesium in the aluminium has emerged as a leading means of reducing the oxide coating, in accordance with the reaction:

$$3Mg + 4Al_2O_3 = 3MgAl_2O_4 + 2Al$$

All of the developed feedstocks have therefore incorporated alloy powders containing magnesium additions (Table 3). The feedstocks also contained a proprietary wax-based binder system, supplied by Ryer Inc. The paper illustrated the capabilities of these feedstocks, using the 6061 type alloy as a case study. It has been demonstrated that the wax-based binder can be debound by solvent,

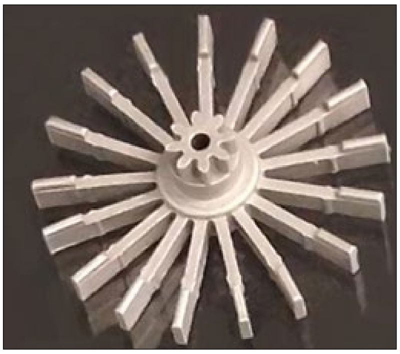

*Fig. 8 A MIM sample part produced with the new 6061 feedstock [3]*

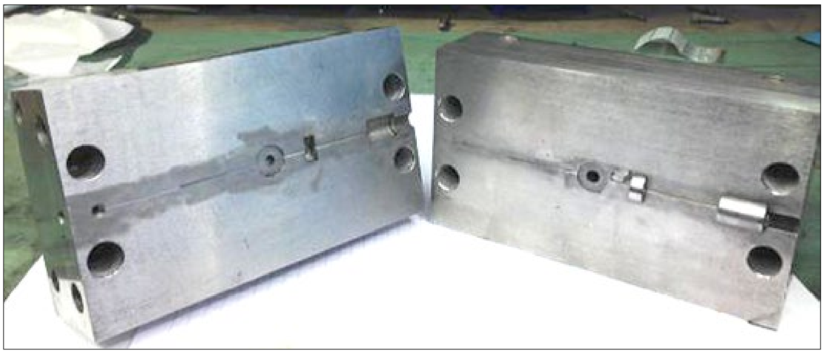

*Fig. 9 Injection mould with lost cavity [4]*

SFE (super critical fluid extraction) or thermal debinding methods. In the thermal debinding process, the binder vaporises and this is considered to be a relatively easy debinding technique.

After debinding, the recommended sintering atmosphere was nitrogen with a dew point of -48°C. A set of sintering trials identified the optimum processing conditions to achieve good sintered properties. The identified sintering temperature range was 640°C - 650°C and the overall processing time was about 8 hours, in which the parts spent about 1-2 hours at the sintering temperature. This sintering temperature range is very close to the melting point of 6061 alloy (652°C) and can cause melting of parts if the temperature is not carefully controlled. Fig. 8 shows a sample sintered at the optimised sintering conditions.

The sintered density of test bars was 2.66 g/cm$^3$, which is about 98.6% of the theoretical density. The average value of as-sintered ultimate tensile strength was around 200 MPa and the Rockwell hardness value was around 93 (B Scale). Tensile bars were also heat treated (T6) at 510°C for 30 minutes, water quenched to ambient temperature and solution treated at 185°C for 8 hours.

The comparison of tensile properties of MIM6061 and wrought alloy 6061 properties are summarised in Table 4. The as-sintered ultimate tensile strength (UTS) value of the MIM6061 was very close to the wrought alloy 6061-T4 value. The 6061-T6 heat treated UTS value was also close to the wrought alloy 6061-T6 value. The authors stated that several MIM part producers around the world are now evaluating these new feedstocks and that they are creating increased general interest in aluminium alloy products in the MIM industry.

| Aluminium MIM Grades | MIM 2024 | MIM 6061 | MIM 7075 |
|---|---|---|---|
| **Chemistry, %:** | | | |
| Silicon | 0.5 Max. | 0.4 – 0.8 | 0.4 Max |
| Iron | 0.5 Max. | 0.5 Max. | 0.5 Max |
| Copper | 3.8 – 4.9 | 0.15 – 0.40 | 1.2 – 2.0 |
| Manganese | 0.3 – 0.9 | 0.15 Max. | 0.30 Max. |
| Magnesium | 1.2 – 1.8 | 0.8 – 1.2 | 2.1 – 2.9 |
| Zinc | | | 5.1 – 6.1 |
| Total others | 1.2 Max. | 1.2 Max. | 1.2 Max. |
| $Al_2O_3$ | <0.5 | <0.5 | <0.5 |
| **Particle Size Distribution:** | | | |
| d50, um | 12 – 18 | 12 – 18 | 12 – 18 |
| d90, um | 34 Max. | 34 Max. | 34 Max. |
| Surface area (BET), m^2/g: | 0.4 Max. | 0.4 Max. | 0.6 Max. |

*Table 3 Properties of MIM alloy grades [3]*

| | MIM-6061 | MIM-6061 | 6061 (Wrought) | 6061 (Wrought) |
|---|---|---|---|---|
| Heat treatment | As sintered | T6 | T4 | T6 |
| Temperature, °C | 640 – 650 | 510 & 177 | | |
| Quenching media | Water | Water | | |
| Ultimate tensile strength, MPa | 190 – 200 | 290 – 300 | 207 – 241 | 290 – 310 |
| Density, g/cm$^{-3}$ | 2.66 | | | |

*Table 4 Mechanical properties of MIM and wrought 6061 alloy [3]*

### W and Re ion emitter-crowns and needles for µN space thruster elements manufactured by MIM

A paper from T Wilfinger, E Feuerstein, M Kitzmantel and E Neubauer (RHP-Technology GmbH, Austria) and M Tajmar (Institute of Aerospace Engineering, TU Dresden, Germany) reported on a study that focused on the manufacture by MIM of W and Re needles (diameter 200-400 µm) and emitter-crowns for µN space satellite thruster elements.

The reported work focused on MIM process development for high aspect ratio (up to 1:200) needle-like porous (~ 25% open porosity) structures made of W or Re. Several feedstock mixtures were prepared to achieve high flowability in order to be able to completely fill the needle structures.

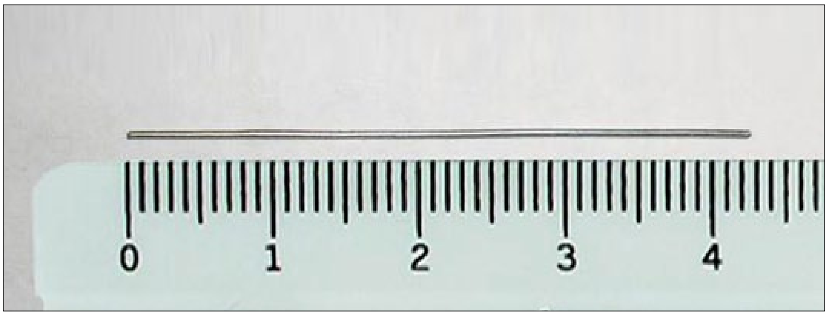

*Fig. 10 Sintered porous W needle [4]*

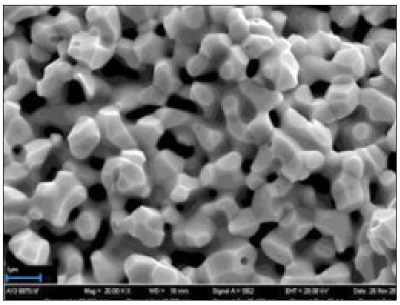
*Fig. 11 SEM of porous W needle [4]*

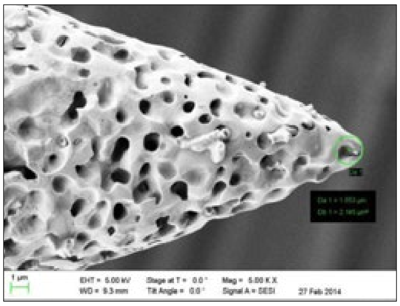
*Fig. 12 Sharpened needle [4]*

The second property to be guaranteed was a complete debinding of the parts at temperatures not exceeding 480°C. Tungsten powders chosen were of particle size 0.8 µm with a purity of 99.8%. The binder system was based on wax with a backbone component of polyethylene. This system shows low viscosity during moulding and allows a high particle loading to ensure full filling of the targeted geometries.

The study highlighted that not only the properties of the binder system determine the success of high aspect ratio filling of moulds, but also the setup of the mould itself has a significant impact. A successful mould setup (Fig. 9) was designed using the system of lost forms. A flexible polymer tube was chosen to be fixed within the mould cavity and used as a strengthening material for the demoulding and handling process. The tubes showed thermal reliability to survive the injection process without any change in geometry and size.

After removing the support tubes by dissolution in concentrated acid, the green W needle parts were stable enough to be manipulated and were placed on alumina based ceramic setters. These setters were then placed in the combined debinding/sintering furnace.

Debinding was conducted under hydrogen atmosphere at a partial pressure of 400 mbar. All polymer components were chosen to evaporate and decompose below 430°C. The debinding process was followed by a sintering segment, where the furnace was ramped to a temperature in the range 1350-1600°C, tailored to achieve the required porosity distribution. The dwell time at sintering temperature was 1-3 hours. The final size of the needles targeted was 43 mm in length and 250-400 µm in diameter, while a residual porosity of 24-27% had to be guaranteed throughout all the material. Fig. 10 shows a sintered W needle and Fig. 11 shows the open porous structure of such a needle.

The porous W needles were subjected to a post-sintering treatment to form the tip structure needed for the application test. This included electrochemically etching (Fig. 12 shows an etched tip) and mounting onto a tantalum reservoir, which contains the propellant, in this case gallium. The result of this wetting procedure is shown in Fig. 13

Manufacture of W crowns and Re emitters showed similar results to those discussed here for the W needles. A detailed investigation of these samples will be followed up in future work.

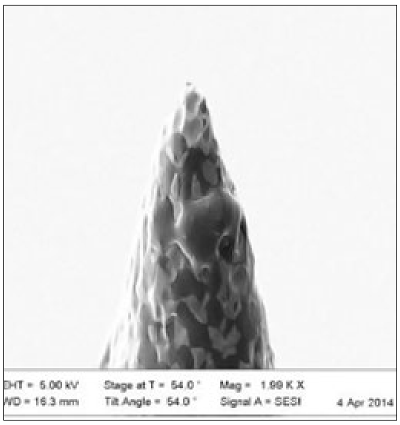
*Fig. 13 Wetted needle (liquid Gallium) [4]*

**Powder Injection Moulding of multi-material devices**

There is significant research activity on PIM of multi-material devices, i.e. the combination of two or more materials with different properties in a single piece manufactured in one process cycle, and the paper from Volker Piotter, Elvira Honza, Alexander Klein, Tobias Mueller and Klaus Plewa (Karlsruhe Institute of Technology (KIT), Germany) highlighted the group's work in this context.

The paper focused on two approaches to achieving the objective: two-component PIM (2C-PIM) and in-mould labelling PIM (IML-PIM). The particular attraction of, but also the challenge for, 2C-PIM relates to obtaining either flexible or permanent joints. For sufficient bond strength, permanent joints must have defined bonding surfaces, for instance between gear wheels and shafts. To ensure that, at the same time, stresses and strains in the two components are avoided or reduced to a minimum the material selection and process procedures must be adapted in such a way that the two components are sintered almost simultaneously i.e., that both components are largely identical with regard to degree of shrinkage and sintering kinetics. If these rules are adhered to, entirely different classes of materials, e.g. steels and ceramics, can be combined. An interesting example

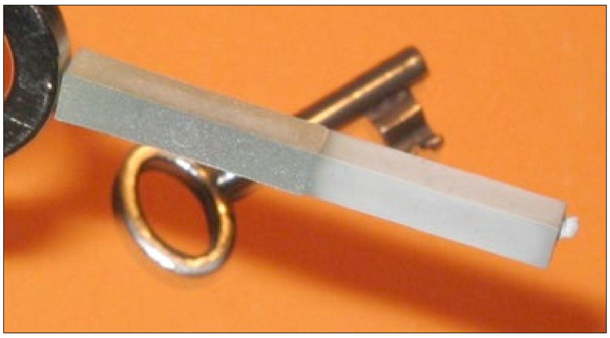

Fig. 14 Fixed connection of metal (stainless steel 430L) and ceramic ($ZrO_2$) materials created by 2C-PIM [5]

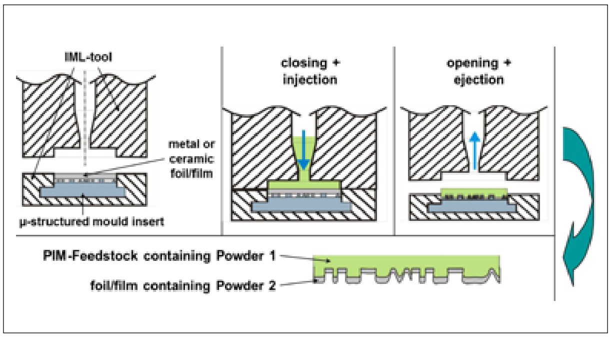


Fig. 15 Illustration of the in-mould labelling process using feedstocks filled with different powder types (IML-PIM) [5]

| Alloy | ρ (g/cm³) | $D_{10}$ (µm) | $D_{50}$ (µm) | $D_{90}$ (µm) |
|---|---|---|---|---|
| Fe49Ni | 8.2 | 4.80 | 11.46 | 36.59 |
| Fe3.8Si | 7.6 | 7.30 | 14.21 | 25.95 |
| Fe35Co | 8.2 | 5.86 | 12.89 | 27.60 |

Table 5 Density and particle size parameters of the soft magnetic alloy powders used [6]

| Alloy | Fe49Ni | Fe3.8Si | Fe35Co |
|---|---|---|---|
| Temperature (°C) | 1360 | 1350 | 1330 |
| Dwell time (h) | 6 | 2 | 3 |
| Heating rate (°C/min) | 5 | 5 | 5 |

Table 6 Sintering conditions [6]

| Material | Relative density (%) Debinding cycle 1 | Relative density (%) Debinding cycle 2 |
|---|---|---|
| Fe49Ni | 95.0 | 93.9 |
| Fe3.8Si | 98.4 | 97.3 |
| Fe35Co | 95.4 | 92.2 |

Table 7 Relative densities of sintered parts [6]

produced by Fraunhofer Institute IKTS was shown (Fig. 14).

For flexible joints, conditions are almost the reverse, i.e. the process parameters and material combinations must be selected in such a way that sintering of the inner partial sections begin earlier than sintering of the surrounding outer sections and that, in addition, the degree of shrinkage of the inner section is higher.

Studies at KIT on two-component shaft-bearing connections have shown that permanent joints can be manufactured reproducibly. Realisation of flexible joints was found to be much more difficult and required, among other things, comprehensive modifications of the composition of the two powder fractions. Only under such conditions and with an appropriate tool design could a gap be formed, enabling rotary motion between the inner (shaft) and outer (bearing) partial sections. KIT have also developed an adaptation of 2C-PIM, involving a successive compaction by pre-sintering and Hot Isostatic Pressing, for the PIM processing of combinations of pure tungsten and tungsten alloys. Following this process route has led to two-component WPIM, which offers the possibility of manufacturing multi-functional parts with reduced assembly steps and without additional brazing. Combinations of pure tungsten with alloyed tungsten or different tungsten alloys have been realised, showing nearly defect-free boundaries. Examples include Nuclear Fusion Reactor components consisting of pure tungsten and tungsten alloys (W-$La_2O_3$, W-$Y_2O_3$).

In-mould labelling PIM uses pre-fabricated inserts in the form of foils or tapes, which are mounted in a tool and subsequently covered by an injection-moulded feedstock layer. By using powder-filled tapes and PIM feedstocks, the fabrication of two- or multi-layered metal or ceramic parts is enabled (Fig. 15). The major challenge, associated with in-mould labelling using powder feedstocks, lies in the development of an adequate sinter process and this challenge is equivalent to that for 2C-PIM of fixed joints. This process has already been investigated for macroscopic applications, using mono-layered tapes as well as staples of foils. The latter approach provides the additional advantage of creating a gradient in the filler content and thus a continuous transition from one section to the other. Trials for adaptation of IML-PIM to micro systems technology are currently running.

## Development of Fe-based soft magnetic alloys by Metal Injection Moulding

A paper from A Paez-Pavon, A Jimenez-Morales and J M Torralba (University Carlos III, Madrid, Spain), T Santos (University Nova of Lisbon, Portugal) and L Quintino (University of Lisbon, Portugal) reported on the development of iron-based soft magnetic alloys processed by MIM.

Using MIM, it is possible to obtain improved soft magnetic materials, compared with the conventional PM route, because of the higher densities obtained. Properties of soft magnetic materials processed by MIM are influenced by density, as a result of powder loading and the debinding and sintering parameters.

The goal of the reported study was to produce Fe-based soft magnetic parts by MIM with optimum magnetic properties using a non-industrialised binder, based on polyolefins. In this work three soft magnetic alloys, Fe-Ni, Fe-Si and Fe-Co, processed by

  

MIM were studied, with a 63 vol% of powder loading used as a preliminary study. The three pre-alloyed powder grades used had the characteristics shown in Table 5.

After moulding, the green parts were debound in two stages, solvent and thermal debinding. Sintering was performed under high vacuum. Sintering parameters are shown in Table 6 and the relative densities obtained in the sintered parts are shown in Table 7. These relative densities were in accordance with typical values reported for MIM processing.

The magnetic field variations along the sintered parts were measured using a Solid State Hall Effect sensor. After the test, the sintered parts were magnetised with a magnetic field of 1100 Gauss for 3 minutes. Fig. 16 shows the magnetic field results. The sintered parts showed good magnetisation homogeneity, because of the constant increase and decrease of the magnetic field along them. Magnetic field along the magnetised samples was higher for Fe-Co alloy, with the maximum field reaching more than 5 Gauss.

The authors concluded that this preliminary work was promising due to low torque values used during the mixing of the feedstocks, which indicates that powder loading could be increased and, as a consequence, final density and mechanical and magnetic properties could be further improved.

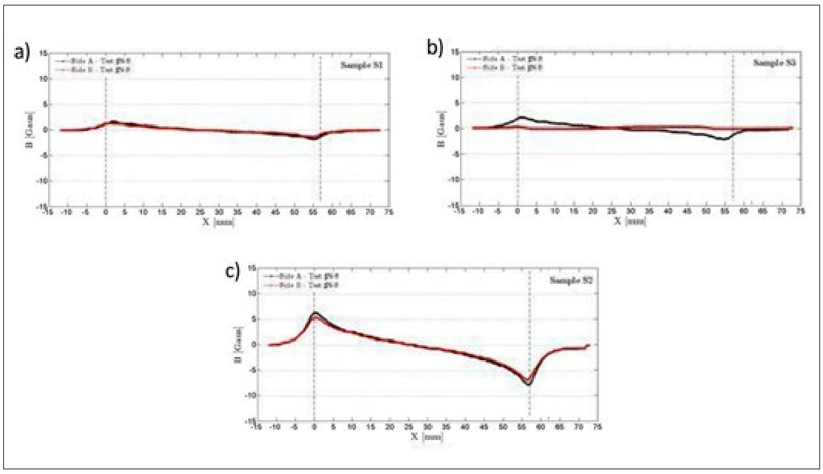

*Fig. 16 Magnetic field along the magnetized sintered parts after thermal debinding cycle 2: (a) Fe49Ni, (b) Fe3.8Si and (c) Fe35Co samples [6]*

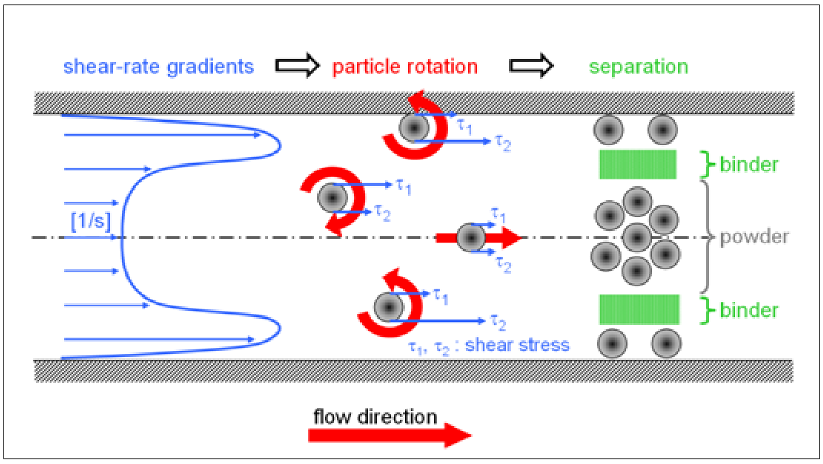


*Fig. 17 Shear-rate gradients; the driving force for segregation [7]*

## Modelling and simulation

**Powder-binder segregation: PIM-simulation at breakthrough**

Four years ago the software company Sigma Engineering GmbH introduced its first generation software for PIM moulding simulation, Sigmasoft, to the market place. This software created an initial breakthrough as accurate simulation of feedstock flow in standard industrial environments became possible. Since then many MIM companies have used simulation results in developing and optimising tools and moulding processes.

This first generation software, however, had no concrete answer to the most urgent issue in PIM: powder-binder segregation. Consequently, Sigma has devoted significant effort into the development of a second generation of Sigmasoft to tackle this limitation. The current status of this development was described in a paper by Gotz Hartmann, Marco Thornagel and Vanessa Schwittay, in a session on PIM Modelling.

Early studies on powder-binder segregation identified shear rate gradients as being a driving force responsible for the segregation (Fig. 17). The first simulation results took the shear induced flux into account. This segregation model worked well for very low particle contents. However, significant limitations were discovered for high particle loadings typical of MIM/CIM feedstocks. It was observed that particles could not escape from the zones of high shear gradient because of the high particle content (55 % - 65 %). The closely packed particles prevented each other from moving to any great extent. This showed that, in addition to the effects forcing powder-binder segregation (i.e. shear rate gradients). there were other effects, which influenced the segregation and even acted in the opposite direction, i.e. forcing particles to remain where they were or even to re-homogenise.

In addition, all these effects couple back to the local viscosity. Fig. 18 shows the relationship between feedstock viscosity and powder loading. The viscosity increases as the powder content increases. While, in the lower powder content regions the viscosity correlates almost linearly with powder concentration, the

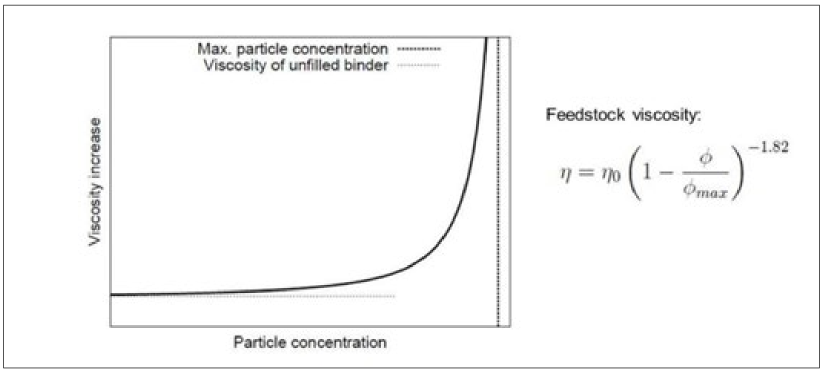


*Fig. 18 The relationship between viscosity and powder loading [7]*

relationship changes to a power-law at high powder concentration. The development of the new generation of Sigmasoft involved entirely new software technology including new solver technology, new meshing technology and a large improvement in speed. Within this new software technology, powder-binder segregation was simulated through its identified dependencies on gradients of shear rate, particle concentration, viscosity and temperature.

The initial validation of the model was based on comparisons with test results from a capillary rheometer, which was used as a test device to investigate local powder concentrations in the feedstock depending on the flow conditions inside the capillary. Flow conditions can be controlled well by the capillary rheometer and the shear rate gradients are in a region relevant for injection moulding processes. Fig. 19 shows the results for particle concentration in a simulated capillary rheometer. The results correspond very well with the findings described in the literature. It can be observed that, in the centre of the capillary, the concentration is close to the initial powder load of 40%. The concentration increases towards the wall and builds to a peak at a short distance from it. Directly at the wall, a thin layer with a very small powder load can be found.

The next step was to test the segregation model in the simulation of a real application. As experimental data quantifying local particle concentration are rarely available, the first approach to testing of the segregation model was focused on the filling pattern. Any significant changes in particle concentration will influence viscosity and thus the flow behaviour, due to the modelled back-coupling of segregation with viscosity.

The part shown in Fig. 20 has been studied extensively in previously reported work and was therefore used again to study the effects of segregation on flow behaviour. Two simulated variants are shown in Fig. 20; one without a back-coupling between particle concentration and viscosity and a second with the new implemented models with this back-coupling included.

Fig. 20 shows the differences between these two variants. When back-coupling between viscosity and particle concentration is included, much higher viscosity values are reached in the middle of the cross section of the part. Here, the particle concentration becomes higher due to shear rate gradients. This effect was not visible in the original model.

Additionally, a change in the general flow behaviour becomes visible when back-coupling is included. When the back-coupling is not taken into account, the melt shows fountain flow behaviour, reaching the T-crossing and, at equal rates, continuing its flow straight-down and to the left. This is a typical behaviour for thermoplastic polymers. However, on taking the back-coupling of segregation with viscosity into account, the flow looks significantly different. Once the melt front reaches the T-crossing, it continues straight-down only; this is also known as plug-flow. There is no flow to the left because of the very high viscosity (the plug) in the centre of the flow channel. This corresponds very well with experimental moulding experience with this part and with additional experience with the same feedstock used in other moulds.

It has now been concluded that

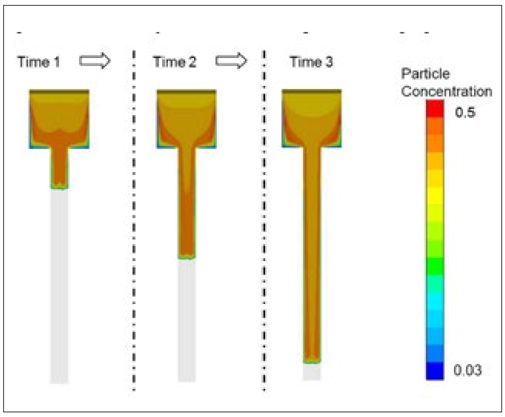


*Fig. 19 Simulated particle concentration within a capillary rheometer [7]*

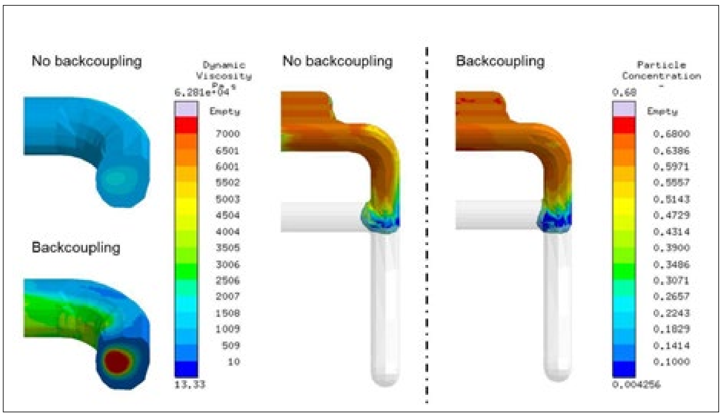


*Fig. 20 Viscosity over the cross section of the part without and with back-coupling (left). Particle concentration and flow behaviour without and with back-coupling (right) [7]*

  

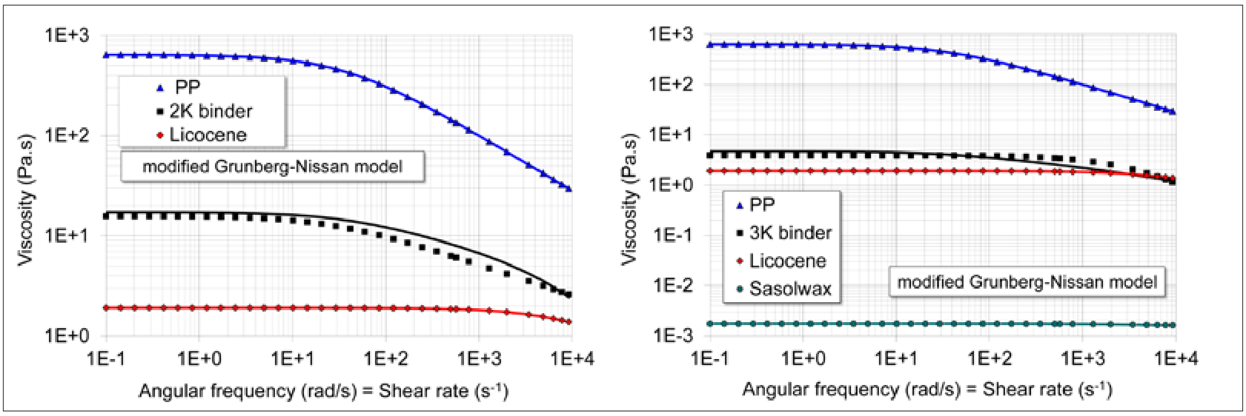


*Fig. 21 Measured and predicted viscosities based on the modified Grunberg-Nissan model: left – 2K-binder system, right – 3K-binder system [8]*

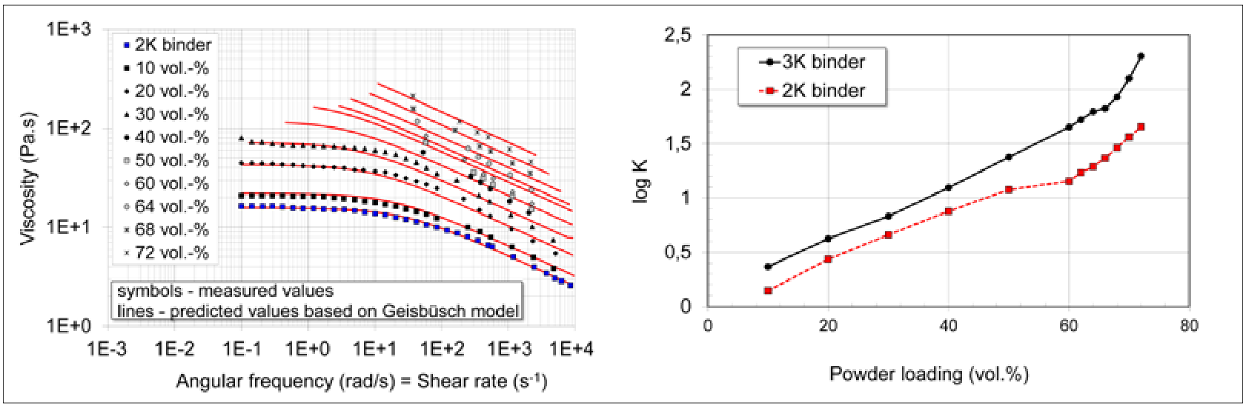


*Fig. 22 Left: measured and calculated viscosities for feedstocks, using the Geisbusch model; right: variation of the factor K in the Geisbusch model with powder loading for the 2K- and 3K-binder systems [8]*

the new model implementations have shown promising results and further model tests with actual MIM applications are continuing.

**Modelling of rheological behaviour of 316L feedstocks with different powder loadings and binder compositions**

Christian Kukla, Ivica Duretek and Clemens Holzer (Montanuniversiteit Leoben, Austria) reported on the modelling of the rheological behaviour of 316L stainless steel feedstocks with different powder loadings and binder compositions.

The binder system plays a large role in the production of PIM parts, even though it is completely removed in the final part. Usually, a binder system consists of different types of polymers, waxes and additives to cover all the functions that a binder system has to fulfil. One of its main functions is to provide mouldability to the metal or ceramic powder. In this context, one of the main properties is viscosity. Knowledge of the dependence of viscosities of binder constituents and powder characteristics on the final composition is required for the solution of many engineering problems.

In the reported study, two different wax based binder systems were investigated; one consisting of two components and one of three components. The powder used was 316L stainless steel with a particle size of 38 µm. The aim was to evaluate mixing rules in predicting the viscosity of the feedstock from its composition.

In relation to the prediction of viscosities of mixtures of liquid polymers in an unloaded binder system, previous work by this group had pointed to the effective use of a modification of an equation, originally developed by Grunberg and Nissan, to incorporate a better description of the transition region from Newtonian to shear thinning behaviour.

Fig. 21 shows the comparisons of measurements and calculations for the 2K- and 3K-binder systems. In both cases, the viscosities of the single components and the final binder system are compared with the approximation based on the modified Grunberg-Nissan model. It can be seen that this model provides a good approximation to the measured data.

In assessing the dependence of the viscosity on the volume concentration of the filler when powder is added to the binder to create the feedstock, a number of models from the literature were evaluated. However, these models all suffered from the deficiency that they do not take into account the fact that the viscosity is a function of shear rate and, related to this, that this function is dependent on the characteristics of the powder, at least on the volume powder content.

 

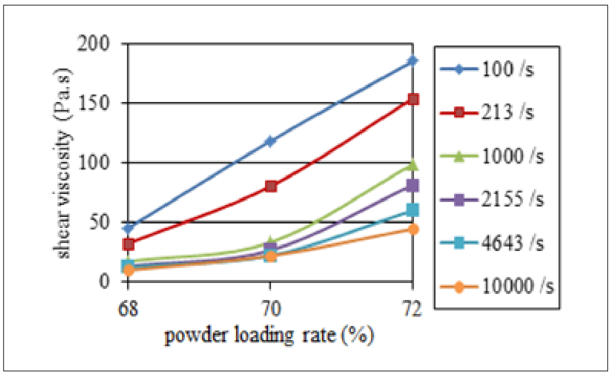


*Fig. 23 Shear viscosity of feedstock vs. powder loading and shear rate for the Inconel feedstocks [9]*

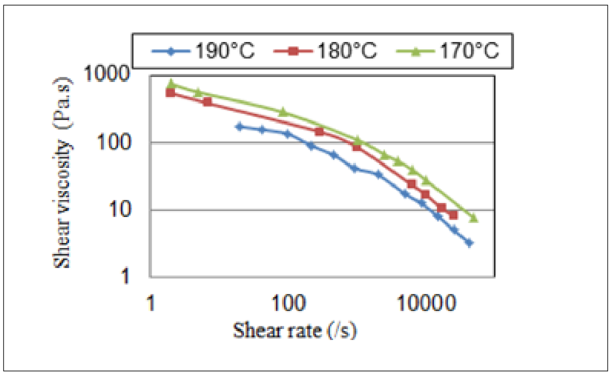


*Fig. 24 Feedstock apparent viscosities at different temperatures [9]*

To tackle this deficiency, a model for highly filled thermoplastics, suggested by Geisbusch, was evaluated. This model is based on the fact that the powder can be regarded as rigid. Therefore, the deformation in a shear field has to be taken by the binder, which means that the binder is sheared more giving a lower viscosity of the binder due to the shear thinning behaviour of a polymer.

Fig. 22 left shows the measured viscosities for a 2K-binder system and the calculated curves using the Geisbüsch model. It can be seen that the transition region is described properly. However, additional effects, such as the change of the slope in the shear thinning region as a function of powder loading cannot be described with this model and further work is necessary to improve the calculation. Fig. 22 right shows the K-factor of the Geisbüsch model for the 2K- and the 3K-binder systems. This factor is higher for the 3K-system, showing a higher increase in shear for the binder due to a higher powder loading. A reason for this could be that the 3K-binder system has the shear thinning region at higher shear rates than the 2K-binder system.

| Component | PP | PEG | SA |
|---|---|---|---|
| Volumetric fraction (%) | 40 | 55 | 5 |

*Table 8 Binder composition [9]*

**Identification of rheological constitutive model adapted for the Powder Injection Moulding process**

The rheology theme was continued in a paper presented by Jean-Claude Gelin, Thierry Barriere and Dimitri Claudel (FEMTO-ST Institute, France). This paper provided a method for determining rheological parameters for constitutive models used for PIM. Numerical simulations require accurate constitutive models describing material behaviour at large shear rates up to $10^5$ $s^{-1}$ and the choice of a rheological model and the determination of its parameters should be made from tests generating such conditions. To identify the rheological constitutive model of feedstocks, this study applied one generalised constitutive law, determined by Hidalgo. The input data for this law comprise parameters derived from the particle size distribution of the powder, the shear apparent density at zero shear rate, the applied shear rate in the test, the critical powder loading and the actual powder loading.

The feedstock studied comprised a nickel-chromium-based superalloy powder added at loadings around 70% to a binder, with the composition shown in Table 8. The rheological properties of the resulting binder formulations and feedstocks were characterised using a capillary rheometer. To measure viscosity curves with the largest possible shear rate range, a rotational rheometer was also employed. This type of rheometer, unlike the capillary rheometer, is suitable for low shear rate measurements. Thus, shear rates varying from 1 to $10^3$ $s^{-1}$ were applied.

The particle size distribution was measured with a laser scattering particle analyser and the specific area was determined using an ASAP2020 accelerated surface area and porosimetry system. To observe the influence of powder loading on viscosity, three feedstocks with different powder

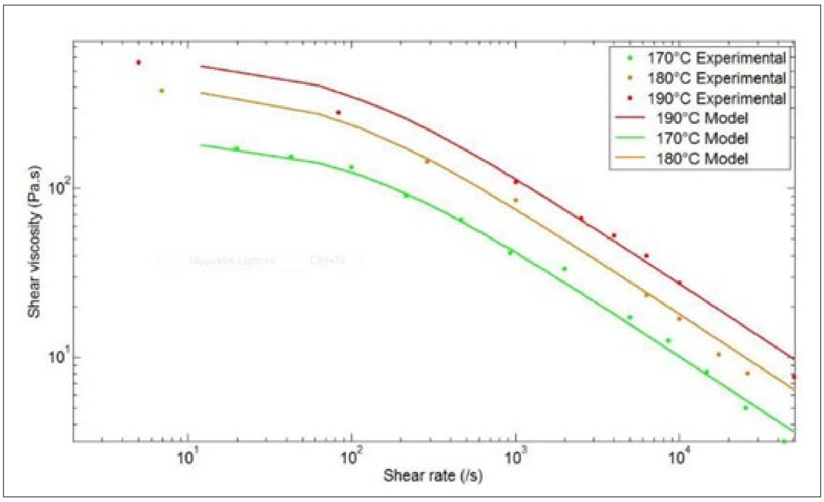


*Fig. 25 Comparisons of experimental results with the predictions from the Hidalgo generalised constitutive law model [9]*

loading rate of 68, 70 and 72% were used. Fig. 23 shows that the shear viscosity increased significantly between the 70% and the 72% powder loading, indicating that the critical powder loading was 72% for the diameter of die used.

The relationship between apparent viscosity and shear rate is shown in Fig. 24 for working temperatures of 170, 180 and 190°C. Shear viscosity decreases with shear rate. This behaviour matches with pseudo-elastic behaviour.

Fig. 25 shows the comparison of these experimental results with the predictions of the Hidalgo generalised constitutive law model. The good agreement between experimental measurements and analytical modelling is clearly demonstrated.

To improve the rheological sensitivity in injection simulations in future work, the authors propose to analyse the influence of a more complex law, in which it will be necessary to take into account the solids loading, shapes and particle sizes of powders and the interaction between powders and binders.

## Author

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[9] J-C Gelin *et al.*, Identification of rheological constitutive model adapted for Powder Injection Moulding process, as presented at Euro PM2014, Austria

# Events Guide

## 2015

**PM15 International Conference & Exhibition**
January 19-21, Mumbai, India
www.pmai.in/pm15/

**MIM 2015**
February 23-25, Tampa, Florida, USA
www.mim2015.org

**PM China 2015 Expo**
April 27-29, Shanghai, China
www.cn-pmexpo.com/en/

**PowderMet2015**
May 17–20, San Diego, CA, USA
www.powdermet2015.org

**AMPM Additive Manufacturing with PM**
(co-located with PowderMet2015)
May 17–19, San Diego, CA, USA
www.ampm2015.org

**Rapid 2015**
May 19-21, Long Beach, California, USA
www.rapid3devent.com

**PM Titanium 2015**
August 31 - September 3, Lüneburg, Germany
www.hzg.de/pmti2015

**Euro PM2015**
October 4-7, Reims, France
www.europm2015.com

**Ceramitec 2015**
October 20-23, Munich, Germany
www.ceramitec.de

**3rd International Conference on Powder Metallurgy in Asia**
November 8-10. Kyoto, Japan
www.apma.asia

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